



Aalborg Universitet

AALBORG UNIVERSITY  
DENMARK

## On the Secondary Control Architectures of AC Microgrids: An Overview

Khayat, Yousef; Shafiee, Qobad; Heydari, Rasool; Naderi, Mobin; Dragicevic, Tomislav; Simpson-Porco, John; Dörfler, Florian; Fathi, Mohammad; Blaabjerg, Frede; Guerrero, Josep M.; Bevrani, Hassan

*Published in:*  
IEEE Transactions on Power Electronics

*DOI (link to publication from Publisher):*  
[10.1109/TPEL.2019.2951694](https://doi.org/10.1109/TPEL.2019.2951694)

*Creative Commons License*  
CC BY 4.0

*Publication date:*  
2020

*Document Version*  
Publisher's PDF, also known as Version of record

[Link to publication from Aalborg University](#)

*Citation for published version (APA):*  
Khayat, Y., Shafiee, Q., Heydari, R., Naderi, M., Dragicevic, T., Simpson-Porco, J., Dörfler, F., Fathi, M., Blaabjerg, F., Guerrero, J. M., & Bevrani, H. (2020). On the Secondary Control Architectures of AC Microgrids: An Overview. *IEEE Transactions on Power Electronics*, 35(6), 6482-6500. [8892668].  
<https://doi.org/10.1109/TPEL.2019.2951694>

### General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal -

### Take down policy

If you believe that this document breaches copyright please contact us at [vbn@aub.aau.dk](mailto:vbn@aub.aau.dk) providing details, and we will remove access to the work immediately and investigate your claim.

# On the Secondary Control Architectures of AC Microgrids: An Overview

Yousef Khayat, Qobad Shafiee, *Senior Member, IEEE*,

Rasool Heydari, Mobin Naderi, Tomislav Dragicevic, *Senior Member, IEEE*, John W. Simpson-Porco, *Member, IEEE*, Florian Dörfler, *Member, IEEE*, Mohammad Fathi, Frede Blaabjerg, *Fellow, IEEE*, Josep M. Guerrero, *Fellow, IEEE*, and Hassan Bevrani, *Senior Member, IEEE*

**Abstract**—Communication infrastructure (CI) in microgrids (MGs) allows for the application of different control architectures for the secondary control (SC) layer. The use of new SC architectures involving CI is motivated by the need to increase MG resilience and handle the intermittent nature of distributed generation units (DGUs). The structure of secondary control is classified into three main categories including centralized SC (CSC) with a CI, distributed SC (DISC) generally with a low data rate CI, and decentralized SC (DESC) with communication-free infrastructure. To meet the MGs operational constraints and optimize performance, control and communication must be utilized simultaneously in different control layers. In this survey, we review and classify all types of SC policies from CI based methods to communication-free policies, including: CSC, averaging based DISC, consensus-based DISC methods, containment pinning consensus, event-triggered DISC, washout-filter based DESC, and state-estimation based DESC. Each structure is scrutinized from the view point of the relevant literature. Challenges such as clock drifts, cyber-security threats, and the advantage of event-triggered approaches are presented. Fully decentralized approaches based on state-estimation and observation methods are also addressed. Although these approaches eliminate the need of any CI for the voltage and frequency restoration, during black start process or other functionalities related to the tertiary layer a CI is required. Power hardware-in-the-loop (PHIL) experimental tests are carried out to compare the merits and applicability of the different SC structures.

**Index Terms**—Centralized control, decentralized control, distributed control, communication-free control, event-triggered control, microgrids, secondary control.

## I. INTRODUCTION

CONTROL objectives in islanded MGs are fulfilled by a hierarchical control platform to set the FaV amplitudes to desired values. PC, SC, and TC are the main control layers which are introduced achieve stability and performance requirements [1]–[4].

Y. Khayat, R. Heydari, T. Dragicevic, F. Blaabjerg, and J. M. Guerrero are with the Department of Energy Technology, Aalborg University, Aalborg, DK, 9220, Denmark (e-mail: ykh@et.aau.dk, rah@et.aau.dk, tdr@et.aau.dk, fbl@et.aau.dk, joz@et.aau.dk).

Q. Shafiee, M. Naderi, M. Fathi, and H. Bevrani are with the Department of Electrical Engineering, University of Kurdistan, Sanandaj, 66177-15175, Iran. (e-mail: q.Shafiee@uok.ac.ir, m.naderi@eng.uok.ac.ir, mfathi@uok.ac.ir, and bevrani@uok.ac.ir).

J. W. Simpson-Porco is with the Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, ON N2L 3G1, Canada (e-mail: jwsimpson@uwaterloo.ca).

F. Dörfler is with the Department of Information Technology and Electrical Engineering, ETH Zurich, 8092 Zurich, Switzerland (e-mail: dorfler@ethz.ch).

## NOMENCLATURE

MG	Microgrid
CI	Communication infrastructure
DGU	Distributed generation unit
CSC	Centralized secondary control
DISC	Distributed secondary control
DESC	Decentralized secondary control
MGCC	Microgrid central controller
PnP	Plug and play
ETC	Event-triggered control
IR	Inertial response
PC	Primary control
SC	Secondary control
EC	Emergency control
AGC	Automatic generation control
TC	Tertiary control
FaV	Frequency and voltage
LPF	Low-pass filter
MAS	multi-agent system
BW	bandwidth
PCC	Point of common coupling
LBCL	Low bandwidth communication link
SoC	State of charge
PHIL	Power hardware-in-the-loop
Variables:	
$G_{LPF}$	Transfer function of the low-pass filter
$\omega^*$	Nominal frequency of the system
$v^*$	Nominal Voltage of the system
$\omega_c$	Cut-off frequency of LPF
$s$	Laplace variable
$\alpha_{ij}$	coupling strength between adjacent DGUs
$\delta u_i$	Correction term forwarded from SC
$K$	Control gain matrix or gain
$x_i(t)$	State variable
$N$	Number of MG's DGUs
$\mathcal{G}$	MG's communication digraph

The first control layer in the hierarchical control platform is the decentralized PC layer, typically consisting of inner current and voltage control loops, a virtual impedance loop, and a droop mechanism controller. Stabilization of the system's FaV amplitudes and power sharing between units are the main control objectives in the PC layer. The FaV stabilization is generally achieved by current and voltage control loops, and power sharing is achieved by the droop control mechanism. Voltage and current loops can also be embedded in a single controller, which can dramatically improve the dynamic performance of the system [5]. The virtual impedance loop as an optional loop acts in MGs with mismatched inductive/resistive feeder impedance, to enhance the power quality and power sharing accuracy of the MG [6]. Droop control is inspired by conventional power systems, and mimics the steady-state

TABLE I. SC POLICIES AND CONTROL STRUCTURES IN AC MGs.

SC Policy	Control Method	References
CSC	Centralized	[30]–[47]
DISC	Averaging	[14], [48]–[56]
	Consensus	[57]–[121]
	Event-triggered	[122]–[134]
DESC	Washout-filter based	[135]–[138]
	Local measurement based	[139]–[145]
	State-estimation / observer based	[146]–[152]

characteristics of a synchronous generator [7]. However, non-droop methods have also been introduced as alternatives [8]–[11].

Steady-state error and FaV amplitude deviations are the drawbacks of the droop control mechanism. Therefore, SC is introduced to eliminate the FaV deviations [12], [13]. Though SC can also be used to improve reactive power sharing accuracy, suppress circulating currents, and harmonic elimination [13], there are fundamental conflicts between accurate reactive power sharing and voltage regulation [14].

Power management and coordination of DGUs at optimal equilibrium points are responsibilities of MGCC, which also determines EC commands due to load-shedding and intentional/unintentional plug in/out of DGUs. Long-term operation concerns such as economic issues and electricity markets are controlled in the global control. Global control and MGCC are located in TC layer in some references [1].

The objective of this survey is to provide an overview of existing SC architectures and to highlight opportunities for future research in this domain. There are some papers that provide a review of the state of the art of MG modelling [15], [16], MG control [17]–[23], MG stability and protection [24], [25], power sharing methods [7], [26], [27], and distributed secondary control [12], [28] with focus on MAS-based approaches [29]. The present survey is distinct from these surveys in that it comprehensively reviews the SC architectures along with their recent challenges. These architectures are categorized into three main classes: CSC, DISC, and DESC. Several approaches are introduced for each class and summarized in Table I.

Compared to the existing surveys, this paper provides the following features:

- A precise SC architecture classification, based on the required communication infrastructure, is presented. It covers not only MASSs, but also decentralized and event-triggered based approaches.
- An investigation on reactive power sharing and how ETC can reduce the required communication BW, based on different event-trigger conditions, is incorporated and compared with general continuous data transmission.
- Time delay effect on DISC and DESC approaches are highlighted, and its malicious effect which leads to instability in DISC approaches are shown.
- Experimental results are carried out to compare the control structures and verify the applicability, merits and drawbacks of different SC architectures.

The rest of this survey begins with the function and time scale of the SC in Section II. Following, the CSC approaches

which mainly focus on harmonic elimination, are analyzed in Section III. In Section IV, the DISC architectures are classified in three main categories based on the CI data transmission, i.e., averaging, consensus, and event-triggered. Moreover, the CI time-delay and clock drifts phenomenon are also considered. In Section V, the DESC architectures are investigated and their challenges are presented. Finally, in Section VIII, we summarize the conclusion remarks of the survey.

## II. TIME-SCALE AND FUNCTION OF THE SC

### A. Time-scale of the Secondary Control in MGs

Unlike the conventional power systems, MGs employ power-electronic interfaces. Although these interfaces are generally fast enough to provide a rapid control response to a disturbance (such as load/generation changes or contingencies), the activated power by DGUs has several limitations [153]. Due to the low inertial feature of MGs and capacity limitations of DGUs, a change in the load has a significant impact on the system operation. For instance, the frequency response of an MG and a huge power system is shown in Fig. 1. When a disturbance is applied at time  $t_0$ , in the conventional power systems the main control design concern is time-scale. In MGs, both time-scale and the amount of activated power need to be considered.

### B. Description of the SC Functions

Droop control adjusts the FaV amplitudes by

$$\omega_i = \omega^* - m_i P_i, \quad P_i = G_{\text{LPF}}(s)p_i, \quad (1a)$$

$$v_i = v^* - n_i Q_i, \quad Q_i = G_{\text{LPF}}(s)q_i, \quad (1b)$$

where  $G_{\text{LPF}}(s) = \omega_c(s + \omega_c)^{-1}$  is a low-pass filter with cutoff frequency  $\omega_c$  for measuring power, and  $p_i$  and  $q_i$  are the instantaneous active and reactive powers, calculated as

$$p_i = v_{\text{od},i} \dot{i}_{\text{od},i} + v_{\text{oq},i} \dot{i}_{\text{oq},i}, \quad (2a)$$

$$q_i = v_{\text{oq},i} \dot{i}_{\text{od},i} - v_{\text{od},i} \dot{i}_{\text{oq},i}, \quad (2b)$$

where  $v_{\text{od},i}$ ,  $v_{\text{oq},i}$ ,  $i_{\text{od},i}$  and  $i_{\text{oq},i}$  are the output voltage and current of DGU $_i$  in the dq frame, respectively. In (1),  $m_i$  and  $n_i$  are the droop controller gains, and  $\omega_i$  and  $v_i$  are the FaV reference values for the inner voltage loop. Obviously, any changes in active and reactive powers will change the FaV reference values. This will lead to steady-state errors and to inaccurate active and reactive power sharing between units.

The role of SC is to eliminate the deviations of  $\omega_i$  and  $v_i$  while simultaneously maintaining the stability of power sharing, voltage, and frequency of the MG. If the set of DGUs in the MG is labeled  $\mathcal{N} = \{1, \dots, N\}$ , then this may be expressed as

$$\lim_{t \rightarrow t_f} \omega_i(t) = \omega^*, \quad (3a)$$

$$\lim_{t \rightarrow t_f} v_i(t) \approx v^*, \quad (3b)$$

$$\lim_{t \rightarrow \infty} (m_i P_i(t) - m_j P_j(t)) = 0, \quad (3c)$$

$$\lim_{t \rightarrow \infty} (n_i Q_i(t) - n_j Q_j(t)) = 0, \quad (3d)$$

for all  $i, j = 1, \dots, N$ , where (3a), (3b), (3c), and (3d) represent frequency restoration and voltage regulation in finite

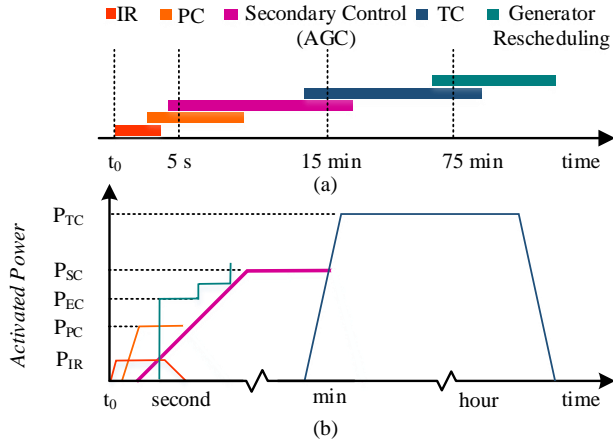


Fig. 1. (a) A typical time-scale of frequency-related dynamics in conventional power systems [154], and (b) activation of frequency control loops following a disturbance at  $t_0$  in an MG [155].

time  $t_f$  and power sharing in steady-state, respectively. In order to share active and reactive power accurately, the voltage values of DGUs must not be perfectly regulated to their reference values, hence the  $\approx$  symbol in (3b) [14].

Another way to formulate the frequency and active power control objectives (3a) and (3c) is in terms of an optimization problem which allocates the secondary control resources of the system. A simple version is given by

$$\underset{P_i}{\text{minimize}} \quad \sum_{i \in \mathcal{N}} \frac{1}{2} m_i P_i^2, \quad (4a)$$

$$\text{subject to} \quad \sum_{i \in \mathcal{N}} P_i = P_{\text{load}}, \quad (4b)$$

where  $P_{\text{load}}$  is the total load in the system. In the problem (4), the quadratic cost (4a) should be minimized subject to balance of active power in the MG, as given by (4b); note that (4b) holds if and only if the frequency objective (3a) holds. It can be shown [88] that the optimal solution of this problem leads to (3a) and (3c). However, this optimization-based perspective allows to specify more sophisticated (non-quadratic) cost functions and constraints giving rise to principled nonlinear controllers achieving the specifications (3) subject to dead-zones, saturations, and alike [120]. We refer to [156], [157] for analogous approaches relating voltage and reactive power control with associated optimization problems.

The SC addresses the above limits by considering a correction term to the droop controller (1) as

$$\omega_i = \omega^* - m_i P_i + \delta u_{\omega,i}, \quad (5a)$$

$$v_i = v^* - n_i Q_i + \delta u_{v,i}, \quad (5b)$$

where  $\delta u_{\omega,i}$  and  $\delta u_{v,i}$  are the control signals forwarded from the SC. Sharing of data — such as FaV and active and reactive power — between DGs can be used to design the SC control signals achieve the control objectives above. In addition, power quality improvement and synchronization (when connecting the MG to the main grid) are other functions introduced under

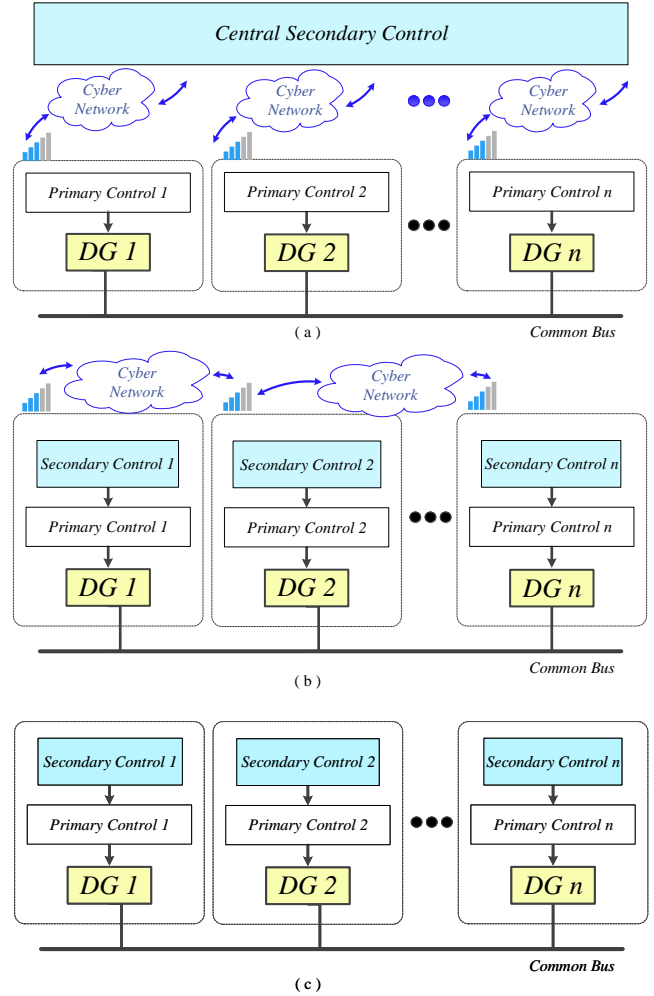


Fig. 2. Three main secondary control architectures: (a) CSC, (b) DISC, and (c) DESC.

the name of SC [87], [119], [158]–[163]. Fig. 2 illustrates centralized SC, DISC, and DESC architectures for achieving this, which will be investigated in the following sections.

### III. CENTRALIZED SECONDARY CONTROL

In the CSC structure, a central controller coordinates the DGs and restores the FaV amplitudes, as shown in Fig. 2(a). However, any failure whether in CI or CSC affects the overall stability and performance of the MG. Active power management, voltage control, reactive power management, frequency restoration and harmonic cancellation are the main features of the CSC. In this structure, all required data, i.e., the DGU's FaV, are generally transmitted through a high data rate CI. Therefore, any deficiency in the CI or failure degrades the MG efficiency.

The main challenges in the CSC architecture have been identified to be harmonic cancellation, unbalanced current reduction, and other power quality and management issues to enhance the system performance. The employed controllers for this architecture with its control goal are tabulated in Table VI. Moreover, its SC is implemented as Fig. 3 to harmonic elimination. Fig. 3 shows the CSC structure for

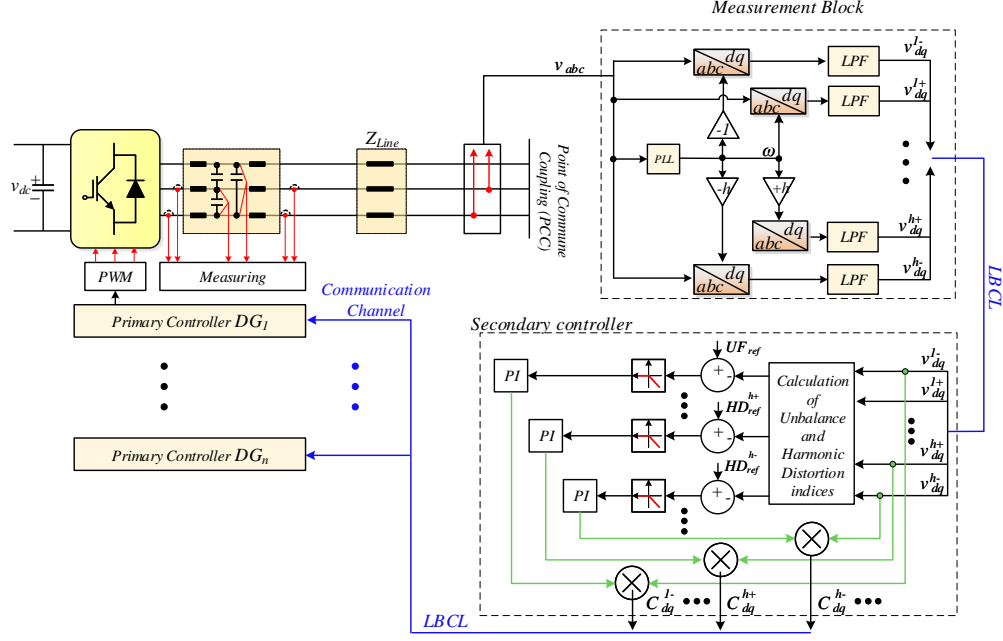


Fig. 3. CSC scheme for voltage unbalance compensation [32].

TABLE II. LITERATURE REVIEW ON CSC GOAL SATISFACTION.

Ref.	Main Contribution	Complexity	Physical Insight	Necessity of Assumption	PnP Verification	Controller type
[30]–[36]	Harmonic cancellation	Low	High	Low	Yes	PI
[36], [43]	Voltage unbalance compensation	Low	Medium	Low	No	PI
[45]	Voltage unbalance compensation	Low	Medium	High	No	Cost Function
[42], [46]	Reactive power management	Medium	Medium	Low	No	Cost Function
[37], [40]	Stability enhancement	High	Medium	Low	No	Adaptive
[41]	SoC considerations in the SC	High	Medium	High	Yes	PI
[44]	Considers model of time delays	Medium	High	low	No	Gain Scheduling
[39]	Incorporates technical constraints	High	High	Low	No	Optimal-Convex

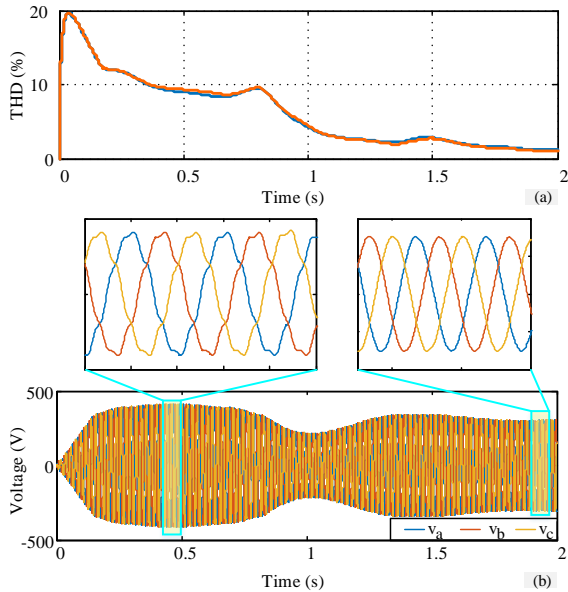


Fig. 4. Harmonic elimination by CSC. (a) Voltage THD reduction, and (b) voltage wave forms.

the harmonic compensation in the studied MG shown in Fig. 10(b). The CSC compensates for the MG harmonics at the point of common coupling (PCC) by sending the harmonic elimination efforts to the DGUs primary controllers through a low bandwidth communication link (LBCL). Fig. 4 shows the simulation results for the harmonic compensation performance of the CSC. As it can be seen, before the CSC activation, the total harmonic distortion (THD) at the PCC is around 10%, while, after CSC activation at  $t=0.75$  s, the THD decrease by 2% which shows the performance of CSC for harmonic compensation.

The CSC architecture is applied in the literature to address harmonic cancellation, unbalanced current reduction, and other power quality and management issues to enhance the system performance. The employed controllers for this architecture with its control goal are tabulated in Table II.

#### IV. DISTRIBUTED SECONDARY CONTROL

As units in a MG are heterogeneous and spatially distributed, distributed control or MAS network controls are a promising approach to enhance MG stability and performance while addressing reliability and enhancing scalability of MGs. In distributed control of MASs, such as an MG, a number of

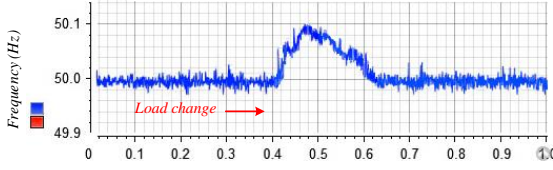


Fig. 5. Frequency restoration applying high BW averaging distributed secondary control structure [49].

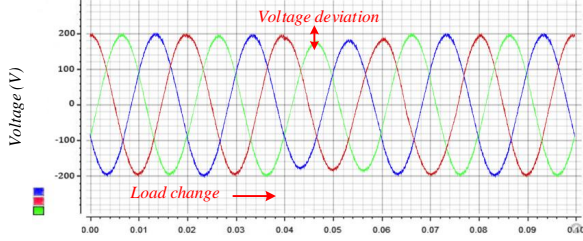


Fig. 6. Voltage recovery applying high BW averaging distributed secondary control structure [49].

DGUs (as agents) work together to cooperatively control the MG and fulfill a set of objectives.

In this case, the behavior of the MG depends on the agent (i.e., DGU) dynamics and the topology of the employed CI. In the following, DISC policies are classified into averaging, distributed consensus, and event-triggered methods.

The basic preliminary for distributed cooperative control is an appropriate knowledge about the CI and its topology. Thus, in this section a brief review on CI modelling and networks are presented, firstly. In an MG system with  $N$  DGUs, which characterized by a state variable  $x_i(t) \in \mathbb{R}^n$  subject to a control input  $u_i(t) \in \mathbb{R}^n$  given as follows:

$$\begin{aligned} \dot{x}_i(t) &= Ax_i(t) + Df(t, x_i(t)) + Bu_i(t), \\ y_i(t) &= Cx_i(t), \end{aligned} \quad (6)$$

where  $i = 1, 2, \dots, N$ , and  $y_i(t)$  stands for the output variables which need to be synchronized or regulated on a desired value. Cooperative control means to implement a distributed protocol by employing the CI such that a desired subset of the state variables can reach an agreement as  $t \rightarrow \infty$ ; that is

$$\lim_{t \rightarrow \infty} \|y_i(t) - y_j(t)\| = 0, \quad \forall i, j = 1, 2, \dots, N. \quad (7)$$

The communication network of an MAS can be expressed by a directed graph (digraph)  $\mathcal{G}$ , which it is usually modelled as  $\mathcal{G} = (\mathcal{V}_{\mathcal{G}}, \mathcal{E}_{\mathcal{G}}, \mathcal{A}_{\mathcal{G}})$  with a nonempty finite set of  $\mathcal{N}$  nodes  $\mathcal{V} = \{\nu_1, \nu_2, \dots, \nu_N\}$ , a set of edges or arcs  $\mathcal{E}_{\mathcal{G}} \subset \mathcal{V}_{\mathcal{G}} \times \mathcal{V}_{\mathcal{G}}$ , and the associated adjacency matrix  $\mathcal{A}_{\mathcal{G}} = [\alpha_{ij}]_{N \times N}$ . In a MG, DGUs are considered as the nodes of the communication digraph, i.e.,  $\mathcal{V}$ , and the edges of the corresponding digraph  $\mathcal{G}$  of the communication network denote the communication links.

#### A. Average-based DISC

In the averaging-based structure, each DGU measures its FaV amplitudes and communicates them to all other DGUs. Let  $x_i$  denote a variable of interest (frequency, voltage, active

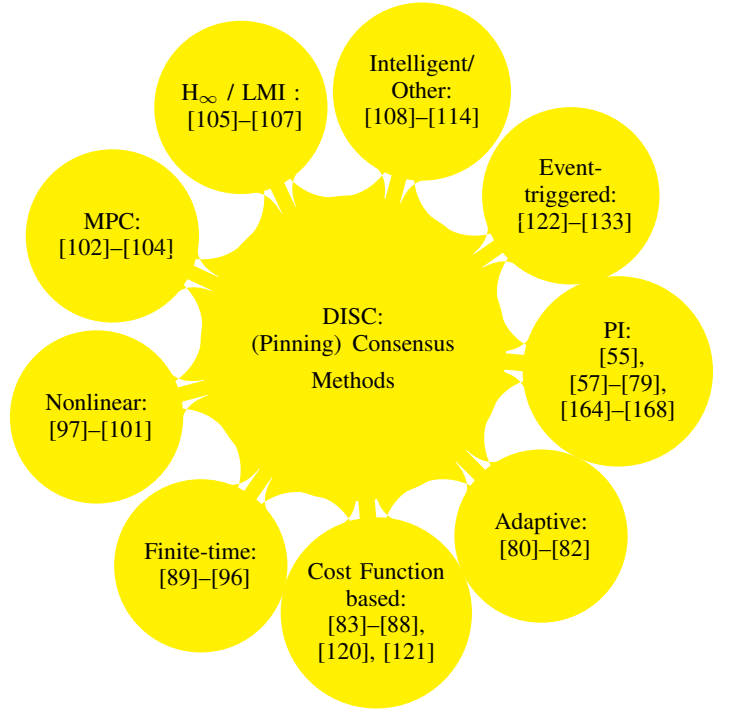


Fig. 7. Distributed consensus secondary control methods.

power, etc.), with nominal value  $x^*$ . By averaging the values received from other DGUs, a control signal can be built as

$$\delta u_i = K_i(s) \left( x^* - \frac{1}{N} \sum_{i \in \mathcal{N}} x_i(t), \right) \quad (8)$$

to form the SC inputs in equation (5) [14], [48]–[51], [53], [54], [88], [120]. The controller  $K_i(s)$  can be designed in different ways (e.g., PI) and tuned for dynamic performance.

Fig. 5 and Fig. 6 show the MG frequency restoration and voltage recovery performance of a high bandwidth averaging DISC proposed in [49], respectively.

#### B. Consensus-based DISC

For MASSs, the CI structure shows the direction and information of the agents as DGUs in a MG. Algorithms leading to agreement among all DGUs are called consensus, agreement, or distributed averaging algorithms [169]. Robustness of this technique is proved in several research works even in the presence of communication delays [44], [53], [116], [121], [170]. In order to restore the FaV in the MG applying the consensus-based techniques, the following distributed protocol is used [14], [55], [88], [164], [168]

$$\delta u_i = K_i(s) \sum_{j \in \mathcal{N}, j \neq i} \alpha_{ij} (x_j(t) - x_i(t)) \quad (9)$$

to produce the control signals in (5). Fundamental performance limitations of such controllers have been examined in [165]–[167]. If the controller  $K_i(s)$  in (11) contains integral control, then in steady-state it will hold that  $x_i = x_j$  for all  $i, j \in \mathcal{N}$ . As a concrete example, this could correspond to active power sharing if  $x_i = m_i P_i$ , which would meet the control objective in (3c). In (11), the coefficients  $\alpha_{ij}$  are nonnegative and are

the elements of the so-called adjacency matrix of the graph describing the CI. DGUs  $i$  receives information from DGU  $j$  if  $\alpha_{ij} \neq 0$ ; see [169] for more details. The summary of methods employing consensus protocols in the SC design procedure is illustrated in Fig. 7.

In order to control an MAS such as an MG converging to a given desired value, the distributed pinning consensus protocol is presented [177]. The term “pinning control” in distributed cooperative control means merely a fraction of nodes in the studied network, which are pinned by the designer to the objective trajectory and the rest of the nodes communicate with each other to achieve the expected networked tracking. A DISC problem is to find correction terms  $\delta u_{v,i}$  and  $\delta u_{\omega,i}$  in (5) such that satisfy (3). To this end, the cooperative objectives can be expressed in terms of the local neighborhood tracking error,

$$e_i = \sum_{j \in \mathcal{N}} \alpha_{ij} (x_j(t) - x_i(t)) - g_i (x_i(t) - x^*), \quad (10)$$

and the correction term can be calculated as:

$$\delta u_i = -cK_i e_i, \quad (11)$$

where  $i = 1, 2, \dots, N$ , the pinning control gain  $g_i \geq 0$  and  $g_i = 0$  shows there is no control over the DGU $_i$ ,  $x^*$  is the desired value for the consensus state  $i$ ,  $c \in \mathbb{R}$  is the coupling gain and  $K_i$  is the feedback control vector. This approach has been employed as pinning-consensus (or leader-following consensus) problems in secondary layer of the MGs. [86], [87], [109], [113],

Unlike the leader-following consensus control, where there exists only one leader in the MG as a MAS, containment control protocol is presented in the presence of multiple leaders and followers in an MAS such as MG [66]. For MGs with many DGUs, conventional consensus is often not sufficient, as the CI topology may be very dynamic. There are many open research challenges in this direction, such as choosing the (optimal) pinned DGUs, convergence rate based on the MG scale, the optimal number of follower DGUs, and switched-CI challenges for networked MGs. The role of containment control can be highlighted in the presence of multiple leaders and multiple followers in an MAS, where the control objective is to bring all the followers into a convex hull spanned by the leaders. The containment control of  $N$  nonlinear agents in (6) with the dynamic of  $i^{th}$  agent can be expressed as follows:

$$\dot{x}_i(t) = Ax_i(t) + Df(t, x_i(t)) + Bu_i(t), \quad i \in \mathcal{V}_{\mathcal{F}} \quad (12)$$

$$\dot{x}_i(t) = Ax_i(t) + Df(t, x_i(t)), \quad i \in \mathcal{V}_{\mathcal{L}} \quad (13)$$

where  $\mathcal{V}_{\mathcal{F}} \triangleq \{1, \dots, M\}$  and  $\mathcal{V}_{\mathcal{L}} \triangleq \{M+1, \dots, N\}$  stand for the followers' and the leaders' sets, respectively. Similar to (11), the containment protocol for the followers in (IV-B) can be calculated as

$$\delta u_i = \sum_{j=1}^N (x_j(t) - x_i(t)), \quad i \in \mathcal{V}_{\mathcal{F}}. \quad (14)$$

Finally, there is a large independent literature developing distributed consensus-based secondary control strategies de-

riving from distributed algorithms to solve the optimization problem (4), see [28, Section IV.C] for a review.

### C. Event-triggered DISC

Over the past years, the ETC has been increasingly employed at the SC level of MG control, as it reduces information exchange among DGUs while retaining stability [122]–[133]. Practically, instead of continuous data exchange among DGUs, the required data can be shared when a criteria is satisfied or an event is triggered. Then, a sampled-data control method is performed, and data is exchanged by a designed mechanism on ETC [171], [184]. As illustrated in Fig. 8, time-triggered, event-triggered, and self-triggered sampling methods are three presented approaches to realize ETC methods.

In time-triggered SC, the control is driven by a clock [185]. This periodic paradigm can be seen as an open-loop sampling (see Fig. 8(a)). In the event-triggered SC, a signal is sent to the SC if an event has occurred, rather than a continuous signal transmission. This can be considered as an introducing feedback in the sampling process (see Fig. 8(b)). It requires the permanent monitoring of the state(s) to determine current performance. Finally, in the self-triggered control, the current state is employed not only to compute the control signal (the input to the system), but it should be calculated the next time for recomputation of control law. Though this mechanism is still closed-loop based on the current performance, permanent monitoring of the state(s) is no longer required (see Fig. 8(c)). A common structure of the ETC can be computed based on the errors between the current instant and the last event of the state variable. The errors are based on the observed and measured value of the state variable [186].

In the ETC designs, the following practical issues should be considered:

1) *Event Mechanism*: Design of a mechanism for event detection is a key challenge for computing event time instants, which directly depends on reducing the recomputation of control law and communication of neighbors. Basically, the structure of the event mechanism should be physically explainable and easy to implement from a practical perspective. As an open research problem, in the MG applications, estimation and observation approaches can be utilized to reduce the employed CI by designing a event mechanism for the SC [187], [188].

2) *Consensus ETC*: If ETC is combined with consensus, the measurements of neighboring DGUs are available only at event time instants. Therefore, an important concern for consensus-ETC designs is how to efficiently employ such information to recompute control law under the designed ETCs. Besides, it is a great challenge to design both the controller in (11) and a threshold-based mechanism for event detection in a unified framework, while the stability of the system must be maintained without occurring Zeno phenomenon.

3) *Zeno Phenomenon*: When the ETC generates an infinite number of sampling instants (events) during a finite time, Zeno phenomenon occurs [189] and makes the solution inapplicable for the real-world systems. This concern should be considered in the control design procedure. To achieve this goal, switching approaches are addressed which by finding a waiting time



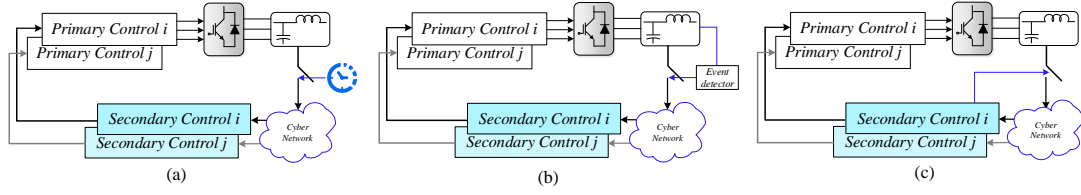


Fig. 8. Event-triggered based distributed secondary control structures: (a) time-triggered DISC, (b) event-triggered DISC, and (c) self-triggered DISC.

TABLE III. TYPICAL ETC MECHANISMS FOR MASS.

	Threshold Mechanism	Ref.	Complexity	BW Reduction (%)
Fixed threshold	$\ e_i(t)\  \geq \delta_i$	[171]	Low	more than 50
Time-dependent threshold	$\ e_i(t)\  \geq c_0 + c_1 e^{-\mu_i(t)t}$	[172]	Medium	more than 70
Continuous state dependent	$\ e_i(t)\  \geq \sigma_i \ X_i(t)\ $	[173]	Medium	more than 70
Sampled state-dependent	$\ e_i(t)\  \geq \sigma_i \ X_i(s_k^i)\ $	[174]	Medium	more than 70
Sampled state-dependent and a positive offset	$\ e_i(t)\  \geq \sigma_i \ X_i(s_k^i)\  + \delta_i$	[175]	High	more than 80
Sampled state-dependent and a time-dependent positive offset	$\ e_i(t)\  \geq \sigma_i \ X_i(s_k^i)\  + c(t)$	[176]	High	$\approx 90$

TABLE IV. CLOCK DRIFT PHENOMENON LITERATURE.

Ref.	SC Policy	Main Achievements	drawbacks
[178]	Without SC	Robust against clock drift	- Huge computations
[179]	Droop free	+ Experimental verification	- Not considered PnP challenges
[180]–[182]	DISC	+ Derive tuning criteria for zero steady-state frequency deviations + Low inertia system is considered + Experimental validation is done	- Not considered sufficient criteria
[183]	DESC	+ PI based DESC investigation	- Not considered PnP challenges - Slow transient response

TABLE V. LITERATURE REVIEW ON DESC GOAL SATISFACTION.

Ref.	DESC type	Controller type	Complexity	Stability Analysis	PnP Verification
[135], [136]	Washout filter-based	(15)	Low	Yes	Yes
[138]	Washout filter-based	(16)	Low	Yes	No
[139]	Local Variable	Time-dependent switched PI	High	Yes	Yes
[143], [144]	Local Variable	Linear quadratic regulator	Low	Yes	Yes
[141]	Local Variable	Integrator based	Medium	No	No
[146]	Nonlinear observer	PI	High	Yes	No
[147]	Observer-based	MPC	High	Yes	No
[149]	Sliding-mode estimator	Averaging integrator	High	Yes	No

guarantees a lower bound for the inter-event times in the event mechanism [190].

In what summarized in Table III, a number of typical ETC mechanisms developed for consensus protocols of MASSs in the existing literature are classified. Nonetheless, we may concentrate on various definitions of the sampling error, e.g., see the tracking error in (10), and threshold without further investigation on their Zeno behavior features because most of them can rule out this phenomenon.

#### D. Problem Based DISC

In this subsection, the works mainly focused on the challenges associated with the SC are presented. These challenges are investigated in the following items.

1) *Voltage stability and reactive power sharing*: Unlike the  $P/\omega$  droop (5a), the power sharing performance of  $Q/v$  droop (5b) is generally unsatisfactory. This is due to the fact that voltage is a local variable, and is in a direct conflict with reactive power. Due to the circulating reactive power and inaccurate reactive power sharing, this issue should be considered in a

conservative manner. This challenge, as another SC function, is addressed in [10], [14], [92], [115]–[117], [119] and [125].

2) *Clock drifts*: A key challenge towards a DGU synchronization, connecting an MG to grid, simultaneous FaV regulation, and accurate power sharing in an MG is the implementation of the designed controller through appropriate hardware. Since each converter in the converter-based MGs operates based on the clock of its processor, a prevalent phenomenon in digital control implementation is clock drift [191]–[193], which may degrade the performance of the system (for example see [194] for recognition of clock synchronization challenges). Because of the popularity of crystal oscillator-based clock processors, with nominal frequency  $f_c$ , a small uncertainty in clock drift makes the clock cycle of the processor as  $\Delta t_c = 1/f_c(1 + \mu)$ , where  $\mu$  is the relative drift of the crystal-oscillator of processor clock [195].

Several papers investigate clock drifts influence on the SC policies. Clock drift phenomenon in the MG was modeled and investigated firstly in [178]. Then, in [63] and [196] a comprehensive analysis of the performance of SC policies with respect to clock drifts are presented. However, all the



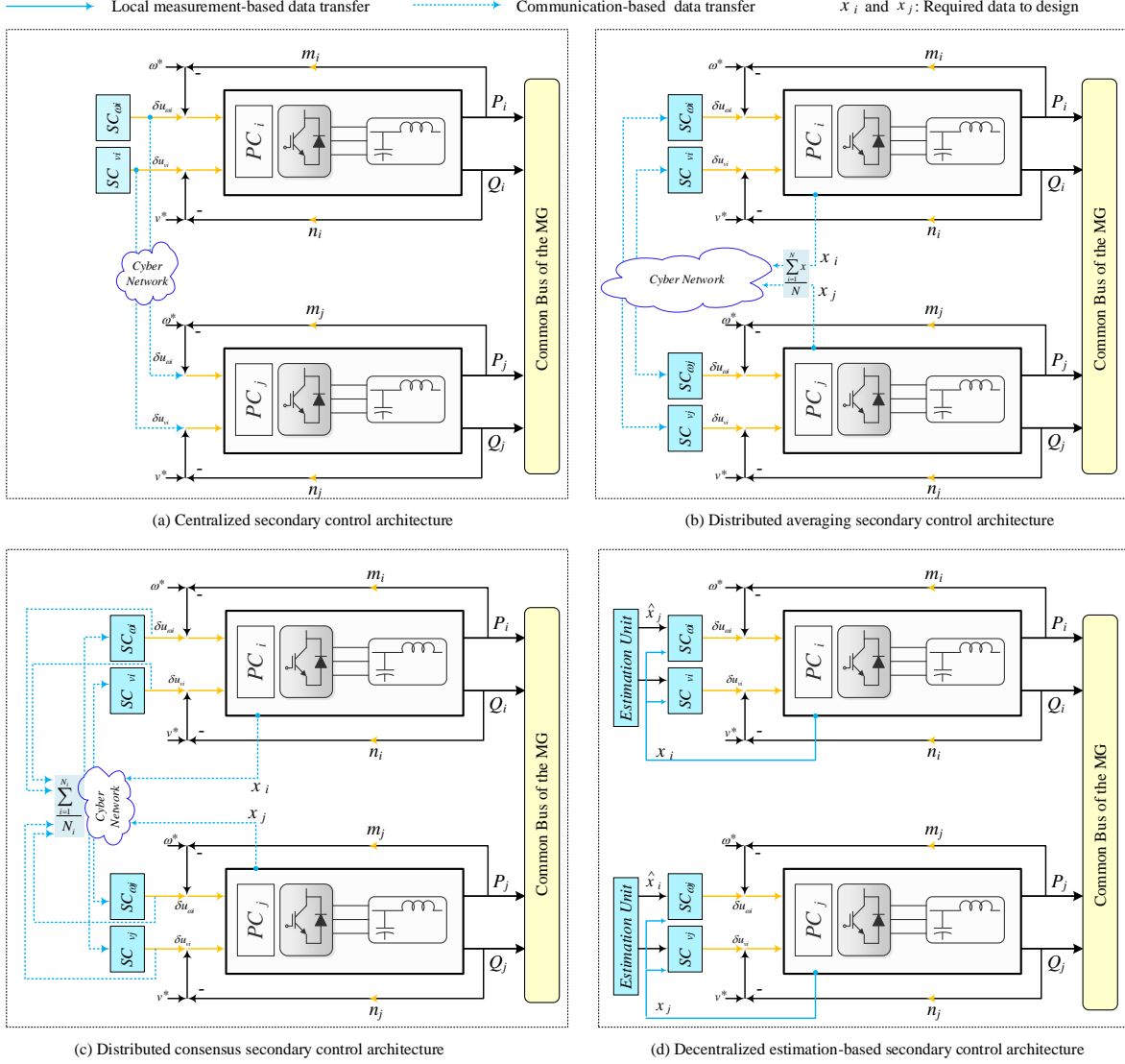


Fig. 9. Secondary control structures: (a) centralized master-slave secondary control, (b) distributed averaging secondary control, (c) distributed consensus secondary control, (d) decentralized estimation based secondary control.

reviewed models are based on the PI controller in Table IV, where the main achievements and drawbacks of clock drift studies are listed. Considering this phenomenon in different secondary controllers and different conditions such as  $PnP$  is an open area for research.

## V. DECENTRALIZED SECONDARY CONTROL

In DESC approaches, CIs are not used for FaV restoration; Each DGU restores its FaV amplitudes to nominal values separately. Although the CI is not applied in the SC operation, the CI is required for transferring data from the TC and MGCC layers [197]. For instance a global CI is required for coordination of the DGUs during black start and PnP processes, real-time monitoring or functionalities of the MGCC, and TC higher control loops. Design procedures employed in this structure are divided into the three main categories, as follows.

### A. Washout Filter-Based DESC

This approach is implemented on the droop control layer, as follows [137]:

$$\omega = \omega^* - m \left( \frac{s}{s + k_p} \right) \left( \frac{\omega_c}{s + \omega_c} \right) p \quad (15a)$$

$$v = v^* - n \left( \frac{s}{s + k_q} \right) \left( \frac{\omega_c}{s + \omega_c} \right) q \quad (15b)$$

If the MG is stable, then by applying the final value theorem to the equations (15), one can show that  $\omega_i$  and  $v_i$  converge to their reference values. A simplified generalized band-pass washout filter SC is introduced in [136] as

$$\omega = \omega^* - \frac{m}{k_{p\omega} + 1} \cdot \underbrace{\frac{\omega_c}{s + \omega_c}}_{\text{low-pass}} \cdot \underbrace{\frac{s}{s + \frac{k_{i\omega}}{k_{p\omega} + 1}}}_{\text{high-pass}} \cdot p \quad (16a)$$

$$v = v^* - \frac{n}{k_{pv} + 1} \cdot \underbrace{\frac{\omega_c}{s + \omega_c}}_{\text{low-pass}} \cdot \underbrace{\frac{s}{s + \frac{k_{iv}}{k_{pv} + 1}}}_{\text{high-pass}} \cdot q. \quad (16b)$$

By adopting appropriate values for the high pass filter as  $k_{p\omega} = k_{pv} = 0$ ,  $k_{i\omega} = k_p$ , and  $k_{iv} = k_q$ , the washout filter based SC (15) can be implemented as well. The generalized band-pass washout filter for the SC is realized by cascading a low-pass filter and a high-pass filter. Its frequency characteristics affect the SC transient response. An analogy between angle droop and frequency droop with new perspectives on virtual impedance regarding the washout filter has been done in [136]. In addition, in [145] the effect of fully decentralized integral control through leaky integral control is studied and the authors provided a comprehensive performance and robustness analysis as well as optimal tuning recommendations for local PI based SC.

A second-order washout filter based power sharing approach for UPS with stability analysis is introduced in [138] for  $Q/\omega$  and  $P/v$  droop control strategy as follows:

$$\omega = \omega^* + n_q \frac{s}{A_\omega s^2 + B_\omega s + C_\omega} \left( \frac{\omega_c}{s + \omega_c} \cdot q \right) \quad (17a)$$

$$v = v^* - m_p \frac{s}{A_v s^2 + B_v s + C_v} \left( \frac{\omega_c}{s + \omega_c} \cdot p \right) \quad (17b)$$

Similar to [145] the effect of fully decentralized second-order washout filter based can be investigated for the future researches by providing a comprehensive performance and robustness analysis as well as optimal tuning of the coefficients of the filter.

### B. Local Variable-Based DESC

In [140] authors used local signals to design a SC without any CI according to a time-dependent protocol. An optimal linear quadratic regulator based DESC for frequency restoration is also presented in [143], [144], [198].

### C. Estimation-Based DESC

Recently, several papers have presented fully DESC schemes utilizing the state estimation methods in autonomous MGs [149]–[152]. To deal with the associated challenges of the global cooperative control in DESC structure, state variable estimation approaches have been recommended [199]–[201]. Recently, a decentralized state estimation method has been introduced for the hybrid AC/DC MGs [150]. Generally, estimation methods deserve significant attention because of their communication-free feature. However, in the MG applications, estimation/observation methods depend on the modelling of

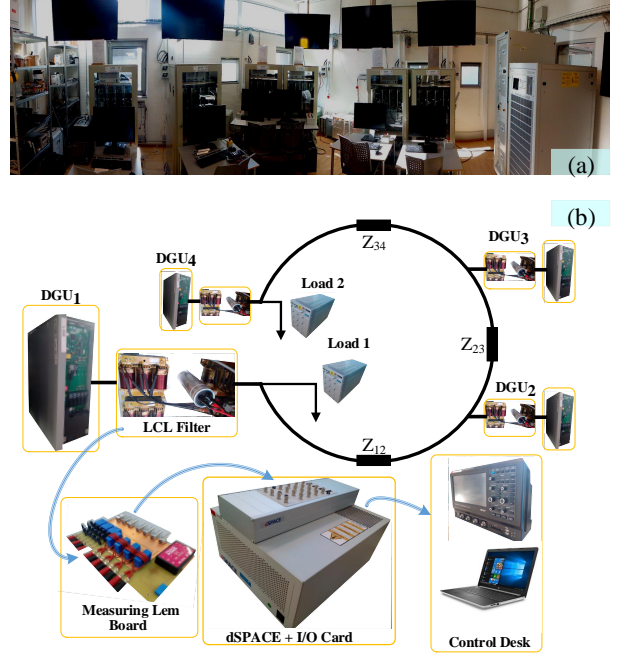


Fig. 10. Laboratory environment and setup circuit diagram. (a) The Center for Research on Microgrids, Aalborg University, Aalborg, and (b) circuit schematic for the experimental tests.

the system. They serve as alternatives to CIs to inform the dynamics of the rest of MG to the local SC units. In addition, [146] and [149] have addressed a nonlinear and Luenberger-like observers for DESC approaches by replacing the measurements in (11) with estimates as

$$\delta u_i = K_i(s) \sum_{j \in \mathcal{N}} \alpha_{ij} (\hat{x}_j - x_i) \quad (18)$$

where  $\hat{x}_j(t)$  is the estimated value of variable  $x_j(t)$  to design the DESC. Specifications of the reviewed DESC approaches are introduced in Table V. In addition, a simple overview of the SC implementation for master-slave, averaging, consensus and estimation based control architectures is demonstrated in Fig. 9. Based on the presented SC architectures, the controller  $K_i(s)$  can be designed considering stability and performance issues.

## VI. RESULT COMPARISON

In order to scrutinize the performance of the defined control structures, an autonomous four-units test MG is implemented. The case study MG comprises four VSCs connected to the common bus through dedicated LC filters shown in Fig. 10. The rated frequency and voltage are 50 Hz and 325 V, respectively. The control parameters and more details of the MG are shown in Table. VI.

Fig. 11(a) and (b) shows the reactive power sharing performance of the consensus based DISC and ETC based DISC (inspired from [125]), respectively. At  $t=12$  s the secondary controller is activated and the reactive power is shared properly among DGUs. In both cases, i.e., consensus based DISC and ETC based DISC, the reactive power sharing is carried on

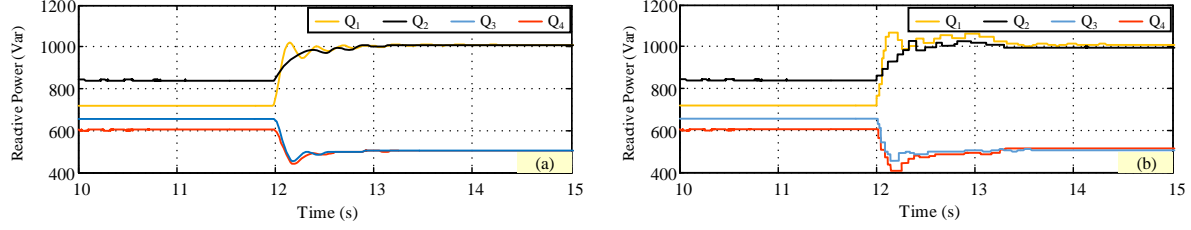


Fig. 11. Reactive power sharing realization. (a) Through a consensus DISC approach presented in [10], and (b) through an event-triggered approach presented in [125].

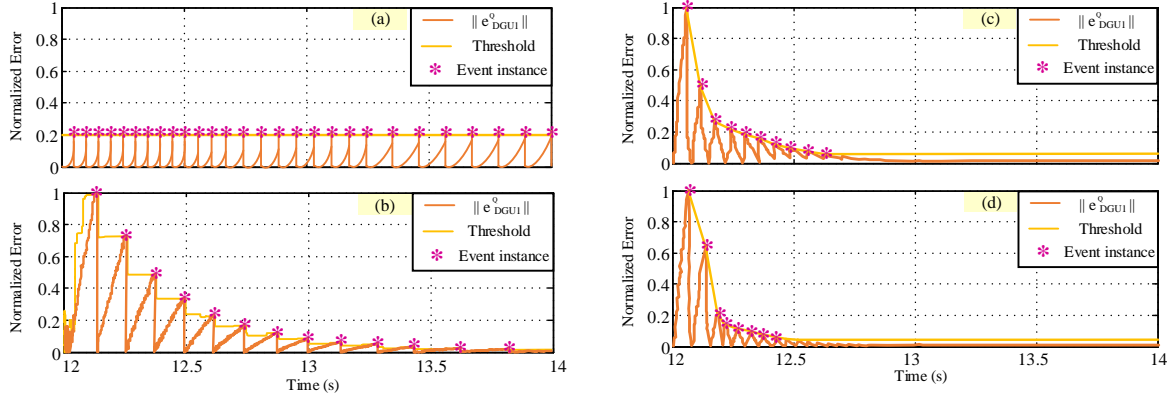


Fig. 12. Evolution of measurement errors of DGU<sub>1</sub> under various ETC's mechanisms: (a) ETC with a fixed threshold, (b) distributed ETC presented in [125] (c) distributed ETC presented in [134], and (d) self-triggered control presented in [134].

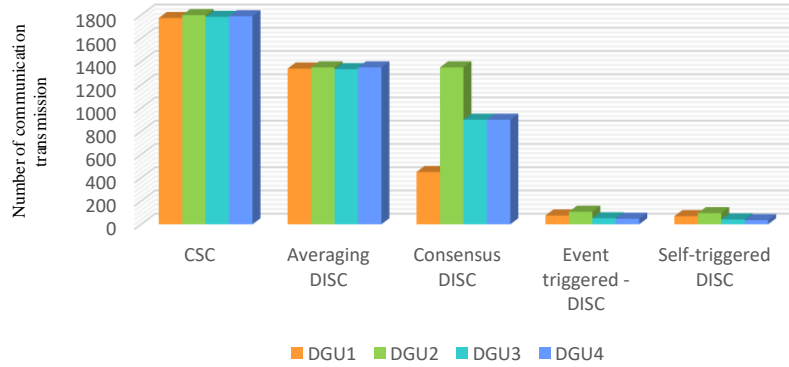


Fig. 13. Communication transmission of the studied MG under the periodic communication scheme with 150 Hz bandwidth for CSC, DISC, event, and self-triggered communication schemes during time interval  $t \in [11 \ 15]$  seconds.

properly. However in ETC based DISC the transmitted data rate is lower than the consensus based DISC. It is worth to note that the reactive power error and its thresholds is illustrated in Fig. 12(b).

Fig. 12 shows evaluation of measurement errors of DGU<sub>1</sub> under four different ETC mechanisms. In order to a fair comparison, all the for mechanisms have been normalized. It is shown how varies the number of events in different ETC structures with a fixed or adaptive thresholds. In Fig. 12(a) a constant threshold is applied, hence, if the error exceed the predefined threshold, an event signal is transferred. In Fig.

12(b) the ETC presented by authors in [125] with its adaptive threshold is applied. As it can be seen, in this ETS structure, the number of transmitted signals and events is lower than constant threshold. Fig. 12(c) and (d) show the self-triggered mechanisms proposed in [134] to decrease the number of transmitted data. In Fig. 13 a comprehensive comparison, in terms of the transmitted data rate and required communication link among CSC and different DISC architectures i.e. Averaging, consensus, event triggered and self triggered is demonstrated. In this case, two signals i.e., reactive power and voltage, are transmitted through different architectures.

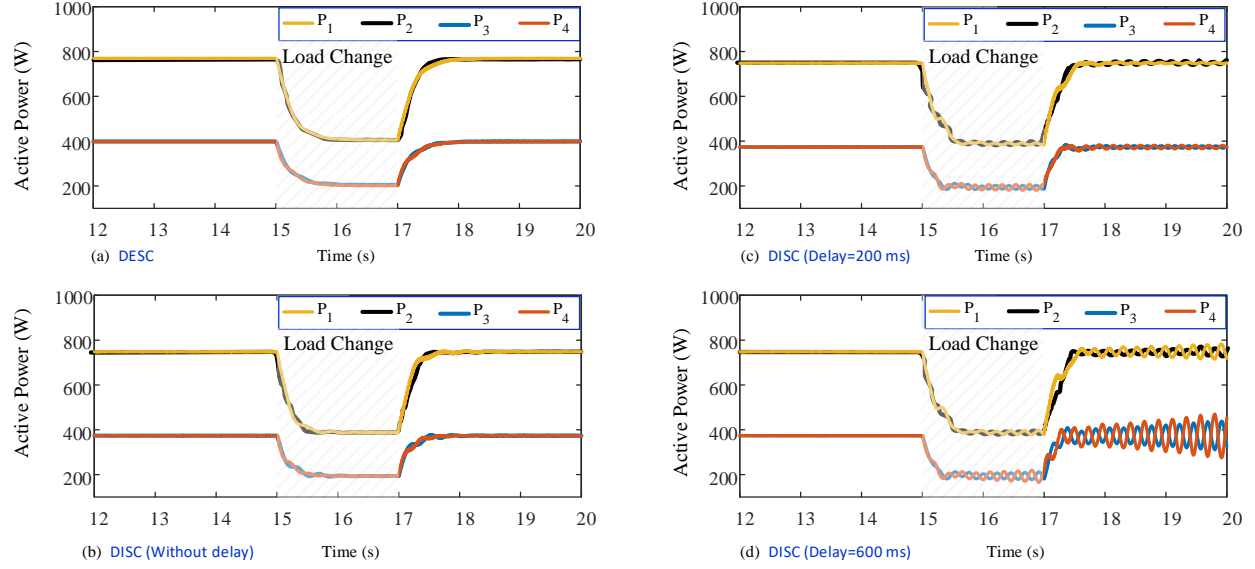


Fig. 14. Performance comparison of decentralized control scheme [144] versus distributed secondary control introduced at [50] by considering communication delay's effect in DISC approaches.

TABLE VI. PARAMETERS OF THE TEST SYSTEM

Electrical Parameters		
Parameters	Symbol	Value
Output voltage of rectifier	$V_{DC}$	650 V
Nominal voltage magnitude	$V_i$	325 V
Nominal Frequency	$f$	50 Hz
Switching Frequency	$f_s$	10 kHz
Capacitance of LCL filter	$C_f$	25 $\mu$ F
Inductances of LCL filter	$L_i / L_o$	1.8 mH
Load 1	$Z_1$	43 $\Omega$ , 0.3 H
Load 2	$Z_2$	124 $\Omega$ , 0.1 H
Line 1	$Z_{12}$	0.4 $\Omega$ , 3.6 mH
Line 2	$Z_{23}$	0.8 $\Omega$ , 1.8 mH
Line 3	$Z_{34}$	0.4 $\Omega$ , 1.2 mH
Inner loop coefficients and other control Parameters		
Control Parameters	DGU: 2 and 4	DGU: 1 and 3
$P - \omega$ droop coefficient	0.001 rad/W.s	0.002 rad/W.s
$Q - v$ droop coefficient	0.005 V/VAr	0.01 V/VAr
Current integral / proportional terms	1000 / 0.5	1000 / 0.5
Voltage integral / proportional terms	120 / 0.05	120 / 0.05
Control design gain $c$	200	200

As can be seen, lower rate of data transmission is required for the event and self triggered DISC, while for the CSC the higher rate of transmitted data is needed.

Fig. 14 shows a comparison between DESC and DISC structure considering communication link time delay. A frequent load change is applied at  $t=15$  s and  $t=17$  s. Fig. 14(a) demonstrates the performance of the DESC structure and Fig. 14(b)-(d) shows the DISC structure performance with different time delays. As the DESC don't need the communication infrastructure, time delay or communication disturbances have no effect on the performance of DESC, while DISC and obviously CSC structures rely on the transmitted data through communication infrastructure. As can be seen from Fig. 14(b)-(d), by increasing the time delay, the control performance of DISC degrades.

## VII. OPEN ISSUE CONCERNS

So far, challenges on event-triggered and pinning consensus methods have been reviewed. More challenges can still be noted in the following.

The effects of malicious cyber-attacks on CI such as denial-of-service [108], [202]–[204], and false-data injection attacks, as well as detection and localization of the attacked nodes and links, and designing appropriate strategies beside the controller should be further considered. In [205] a review of cyber attacks for the power system is presented, which can be also applied on the MG. The promise of observer/estimator based controllers, in order to achieve stability margins and reliability of the system under diverse uncertainty, will introduce new SC architectures for the MG.

References [206] and [207] provide an approach towards observability and controllability analysis of the networked linear systems subject to data losses. However, the time-varying delays introduce negative effect on DGU synchronization after  $PnP$  scenarios. This issue requires further research. Another generally open issue is the performance and robustness of secondary MG controllers, when the system is driven by measurement noise and disturbances.

Multi-MG structures are also introduced as a more resilience solution, which can have a static or dynamic topology and interconnect on a same distribution feeder. The main difference between the static and dynamic multi-MG is that the dynamic multi-MGs have a changing point of interconnection. This can be realized by smart static switches. Fig. 15(a) shows a static multi-MG in which they can be networked with each other by a static switch located in the common bus. Figs. 15(b) and 15(c) show two possible topology of a dynamic multi-MG. As it can be seen, the multi-MGs topology can change based on the static switch situation. Another classification of Multi-

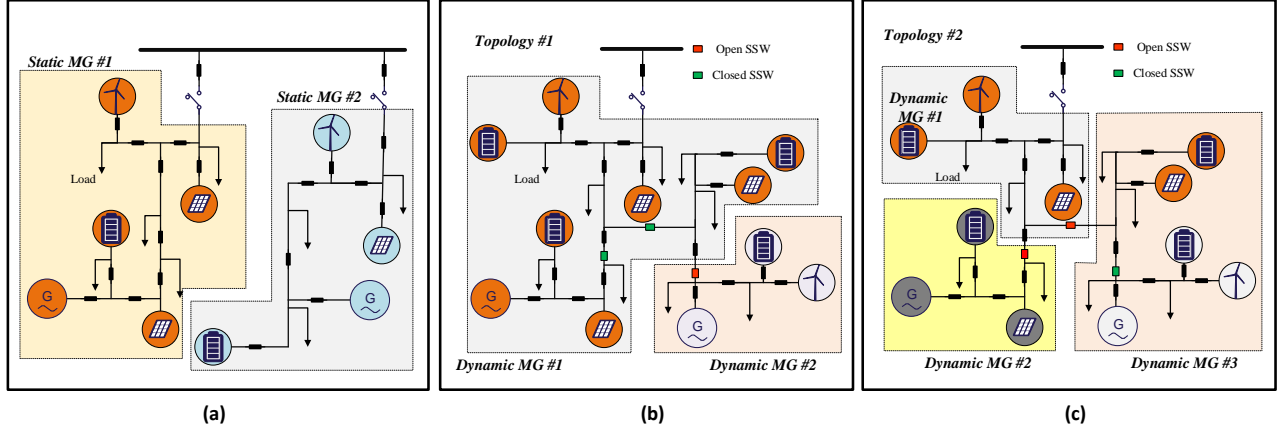


Fig. 15. Static and dynamic architectures of multi-MG systems. (a) A static multi-MG system, (b) topology 1 of a dynamic multi-MG system employing smart SSWs, and (c) topology 2 of a dynamic multi-MG system employing smart static switches.

MG systems can be done based on the interlink devices and how MGs are connected with each other. However, multi-MGs can be networked by controllable circuit breakers (CBs), e.g., smart switches (SSWs) with cost-efficient reasons, back-to-back converters (BTBCs) are another solution which can be employed for implementing extra functionalities by cooperative control approaches. Networked multi-MGs through power electronic interfaces can be constructed in various structures. AC-DC Multi-MGs, AC-DC interlinking lines, interlinking devices, distributed and decentralized control, as well as communication methods, lead to different Multi-MG structures. Apart from the stability analysis/requirements within a multi-MG cluster, the distributed cooperation among multiple-MG clusters is also essential to increase the reliability of the whole multi MG-cluster system. In this way each MG will be able to absorb power from its neighbors in an emergency situation. To this end, several works have been done, which employed decentralized/distributed secondary control approaches [208]. Self-healing capability of the distribution system after extreme faults by designing a control framework for multi-MG systems, robust distributed control for more resilient energizing, and power exchange strategies based on the instantaneous static switch are some examples of control methods that can be performed in secondary layer to improve the power exchange among multi-MG systems. Nevertheless, the important role of secondary control either in distributed or decentralized manners for more resilience and improve the power exchange is not addressed properly. Reducing the communication infrastructure by self-triggered, event-triggered, or even decentralized approaches leads to a more secure-resilience multi-MG system, which needs to employing efficient cyber-control study as open issues to shed light.

### VIII. CONCLUSION

This paper presented an overview of the secondary control structures in the hierarchical control of autonomous MG. In order to improve the reliability, energy management of the MG, centralized SC is established. CSC is reviewed in detail

and merits and drawbacks of this structure, such as communication deficiencies, have also been summarized. Due to the single point of failure of the centralized structure, distributed structure is presented. DISC strategies are categorized based on different communication structures and transmitted data into the three main topologies: averaging based, consensus-based, and event triggered based approaches. However, in consensus structure, with increasing the number of DGUs, new concerns are revealed and stated as open issues. Furthermore, event based DESC structures, configurations and formulations are scrutinized. Finally, DESC structures which are entirely communication-free are presented. Design procedures employed in this structure are divided into the three main categories, i.e., washout filter based, local variable based and estimation based approaches. Although DESC structure have no communication challenges, i.e., CI delay and data dropout, in order to achieve a comprehensive control, an accurate estimation of neighbour DGUs variable is required. Voltage stability, reactive power sharing, and clock drift challenges of SC for experimental implementations are also summarized. Finally, a comprehensive comparison, as well as control design challenges, formulations and open issue concerns have been presented.

### IX. APPENDIX

The communication links of the studied MG for the consensus DISC and ETC-DISC is given as follows:

$$\mathcal{A}_g = [\alpha_{ij}]_{4 \times 4} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 1 & 1 \\ 0 & 1 & 0 & 1 \\ 0 & 1 & 1 & 0 \end{bmatrix}.$$

By a simplified  $Q-v$  dynamics for DGU<sub>*i*</sub>, given as:

$$\begin{aligned} \dot{V}_i &= u_i \\ Q_i &= |B_{ii}|V_i^2 - \sum_{m \in \mathcal{N}} |B_{im}|V_iV_j \end{aligned} \quad (19)$$

where  $V_i$  is the output voltage amplitude of DGU<sub>*i*</sub>;  $u_i$  is the control effort;  $B_{ii}$  is the shunt susceptance of DGU<sub>*i*</sub>. In



[125] an ETC-DISC for proportional reactive power sharing is formulated by

$$u_i(t) = -\frac{\kappa}{\chi_i} V_i(t) \sum_{j \in \mathcal{N}} \alpha_{ij} \left( \frac{Q_i(t_{k_i}^i(t))}{\chi_i} - \frac{Q_j(t_{k_j}^j(t))}{\chi_j} \right) \quad (20)$$

where  $k_i(t) \triangleq \arg \max_k \{t_k^i | t_k^i \leq t\}$ ,  $\chi_i$  and  $\chi_j$  stand for the  $Q-v$  droop coefficients of  $\text{DGU}_i$  and  $\text{DGU}_j$ . The ETC, which determines the event times  $t_k^i$  of  $\text{DGU}_i$ , was designed as

$$|e_i(t)| \leq \eta \chi_i \left| \sum_{j \in \mathcal{N}} \alpha_{ij} \left( \frac{Q_i(t_{k_i}^i(t))}{\chi_i} - \frac{Q_j(t_{k_j}^j(t))}{\chi_j} \right) \right| \quad (21)$$

where  $e_i(t) = Q_i(t_k^i) - Q_i(t)$ ,  $Q_i(t_k^i)$  stands for the transmitted measurement of  $Q_i(t)$  at the event time instant  $t_k^i$ ,  $k \in \mathcal{N}$ , and  $\eta$  is a positive constant and its maximum value can be chosen lower than the maximum eigenvalues of Laplacian matrix  $\mathcal{A}_g$ .

## REFERENCES

- [1] H. Bevrani, B. François, and T. Ise, *Microgrid dynamics and control*. John Wiley & Sons, 2017.
- [2] F. Blaabjerg, *Control of Power Electronic Converters and Systems*. Academic Press, 2018, vol. 2.
- [3] M. Naderi, Y. Khayat, Y. Batmani, and H. Bevrani, "Robust multivariable microgrid control synthesis and analysis," *Energy Procedia*, vol. 100, pp. 375–387, 2016.
- [4] J. M. Guerrero, J. C. Vasquez, J. Matas, L. G. De Vicuña, and M. Castilla, "Hierarchical control of droop-controlled ac and dc microgrids: a general approach toward standardization," *IEEE Trans. Ind. Electron.*, vol. 58, no. 1, pp. 158–172, 2011.
- [5] T. Dragičević, "Model predictive control of power converters for robust and fast operation of ac microgrids," *IEEE Trans. on Power Electron.*, vol. 33, no. 7, pp. 6304–6317, 2018.
- [6] X. Wang, Y. W. Li, F. Blaabjerg, and P. C. Loh, "Virtual-impedance-based control for voltage-source and current-source converters," *IEEE Trans. Power Electron.*, vol. 30, no. 12, pp. 7019–7037, 2015.
- [7] Y. Han, H. Li, P. Shen, E. A. A. Coelho, and J. M. Guerrero, "Review of active and reactive power sharing strategies in hierarchical controlled microgrids," *IEEE Trans. Power Electron.*, vol. 32, no. 3, pp. 2427–2451, 2017.
- [8] V. Nasirian, Q. Shafiee, J. M. Guerrero, F. L. Lewis, and A. Davoudi, "Droop-free distributed control for ac microgrids," *IEEE Trans. Power Electron.*, vol. 31, no. 2, pp. 1600–1617, 2016.
- [9] Z. Wang, W. Wu, and B. Zhang, "A distributed quasi-newton method for droop-free primary frequency control in autonomous microgrids," *IEEE Trans. Smart Grid*, vol. 9, no. 3, pp. 2214–2223, 2018.
- [10] Q. Shafiee, V. Nasirian, J. C. Vasquez, J. M. Guerrero, and A. Davoudi, "A multi-functional fully distributed control framework for ac microgrids," *IEEE Trans. Smart Grid*, vol. 9, no. 4, pp. 3247–3258, 2018.
- [11] B. Johnson, M. Sinha, N. Ainsworth, F. Dörfler, and S. Dhople, "Synthesizing virtual oscillators to control islanded inverters," *IEEE Trans. Power Electron.*, vol. 31, no. 8, pp. 6002–6015, 2016.
- [12] M. Yazdani and A. Mehrizi-Sani, "Distributed control techniques in microgrids," *IEEE Trans. Smart Grid*, vol. 5, no. 6, pp. 2901–2909, 2014.
- [13] D. E. Olivares, A. Mehrizi-Sani, A. H. Etemadi, C. A. Cañizares, R. Iravani, M. Kazerani, A. H. Hajimiragha, O. Gomis-Bellmunt, M. Saeedifard, R. Palma-Behnke *et al.*, "Trends in microgrid control," *IEEE Trans. Smart Grid*, vol. 5, no. 4, pp. 1905–1919, 2014.
- [14] J. W. Simpson-Porco, Q. Shafiee, F. Dörfler, J. C. Vasquez, J. M. Guerrero, and F. Bullo, "Secondary frequency and voltage control of islanded microgrids via distributed averaging," *IEEE Trans. Ind. Electron.*, vol. 62, no. 11, pp. 7025–7038, 2015.
- [15] M. S. Mahmoud, S. A. Hussain, and M. A. Abido, "Modeling and control of microgrid: An overview," *Journal of the Franklin Institute*, vol. 351, no. 5, pp. 2822–2859, 2014.
- [16] J. Schiffer, D. Zonetti, R. Ortega, A. M. Stanković, T. Sezi, and J. Raisch, "A survey on modeling of microgrids from fundamental physics to phasors and voltage sources," *Automatica*, vol. 74, pp. 135–150, 2016.
- [17] E. Unamuno and J. A. Barrena, "Hybrid ac/dc microgrids part ii: Review and classification of control strategies," *RENEW. SUST. ENERG. REV.*, vol. 52, pp. 1123–1134, 2015.
- [18] A. Bidram and A. Davoudi, "Hierarchical structure of microgrids control system," *IEEE Trans. Smart Grid*, vol. 3, no. 4, pp. 1963–1976, 2012.
- [19] E. Planas, A. Gil-de Muro, J. Andreu, I. Kortabarria, and I. M. de Alegria, "General aspects, hierarchical controls and droop methods in microgrids: A review," *RENEW. SUST. ENERG. REV.*, vol. 17, pp. 147–159, 2013.
- [20] P. Monica and M. Kowsalya, "Control strategies of parallel operated inverters in renewable energy application: A review," *RENEW. SUST. ENERG. REV.*, vol. 65, pp. 885–901, 2016.
- [21] A. M. Bouzid, J. M. Guerrero, A. Cheriti, M. Bouhamida, P. Sicard, and M. Benghanem, "A survey on control of electric power distributed generation systems for microgrid applications," *RENEW. SUST. ENERG. REV.*, vol. 44, pp. 751–766, 2015.
- [22] K. Rajesh, S. Dash, R. Rajagopal, and R. Sridhar, "A review on control of ac microgrid," *RENEW. SUST. ENERG. REV.*, vol. 71, pp. 814–819, 2017.
- [23] A. Kaur, J. Kaushal, and P. Basak, "A review on microgrid central controller," *RENEW. SUST. ENERG. REV.*, vol. 55, pp. 338–345, 2016.
- [24] Z. Shuai, Y. Sun, Z. J. Shen, W. Tian, C. Tu, Y. Li, and X. Yin, "Microgrid stability: Classification and a review," *RENEW. SUST. ENERG. REV.*, vol. 58, pp. 167–179, 2016.
- [25] P. Basak, S. Chowdhury, S. H. nee Dey, and S. Chowdhury, "A literature review on integration of distributed energy resources in the perspective of control, protection and stability of microgrid," *RENEW. SUST. ENERG. REV.*, vol. 16, no. 8, pp. 5545–5556, 2012.
- [26] K. E. Antoniadou-Plytaria, I. N. Kouveliotis-Lysikatos, P. S. Georgilakis, and N. D. Hatzigiorgiou, "Distributed and decentralized voltage control of smart distribution networks: models, methods, and future research," *IEEE Trans. Smart Grid*, vol. 8, no. 6, pp. 2999–3008, 2017.
- [27] H. Han, X. Hou, J. Yang, J. Wu, M. Su, and J. M. Guerrero, "Review of power sharing control strategies for islanding operation of ac microgrids," *IEEE Trans. Smart Grid*, vol. 7, no. 1, pp. 200–215, 2016.
- [28] D. K. Molzahn, F. Dörfler, H. Sandberg, S. H. Low, S. Chakrabarti, R. Baldick, and J. Lavaei, "A survey of distributed optimization and control algorithms for electric power systems," *IEEE Trans. Smart Grid*, vol. 8, no. 6, pp. 2941–2962, 2017.
- [29] Y. Han, K. Zhang, H. Li, E. A. A. Coelho, and J. M. Guerrero, "Mas-based distributed coordinated control and optimization in microgrid and microgrid clusters: A comprehensive overview," *IEEE Trans. Power Electron.*, vol. 33, no. 8, pp. 6488–6508, 2018.
- [30] M. Savaghebi, J. M. Guerrero, A. Jalilian, and J. C. Vasquez, "Secondary control for voltage unbalance compensation in an islanded microgrid," in *Smart Grid Commun. (SmartGridComm)*, IEEE Int. Conf. on. IEEE, 2011, pp. 499–504.
- [31] M. Savaghebi, A. Jalilian, J. C. Vasquez, and J. M. Guerrero, "Secondary control scheme for voltage unbalance compensation in an islanded droop-controlled microgrid," *IEEE Trans. Smart Grid*, vol. 3, no. 2, pp. 797–807, 2012.
- [32] —, "Secondary control for voltage quality enhancement in microgrids," *IEEE Trans. Smart Grid*, vol. 3, no. 4, pp. 1893–1902, 2012.
- [33] P. N. Vovos, A. E. Kiprakis, A. R. Wallace, and G. P. Harrison, "Centralized and distributed voltage control: Impact on distributed generation penetration," *IEEE Trans. Power Syst.*, vol. 22, no. 1, pp. 476–483, 2007.
- [34] X. Wang, J. M. Guerrero, F. Blaabjerg, and Z. Chen, "Secondary voltage control for harmonics suppression in islanded microgrids," in *Power and Energy Soc. General Meeting, IEEE*. IEEE, 2011, pp. 1–8.
- [35] M. H. Andishgar, E. Gholipour, and R.-A. Hooshmand, "Voltage quality enhancement in islanded microgrids with multi-voltage quality requirements at different buses," *IET GENER. TRANSM. DIS.*, vol. 12, no. 9, pp. 2173–2180, 2018.
- [36] Y. Han, P. Shen, X. Zhao, and J. M. Guerrero, "An enhanced power sharing scheme for voltage unbalance and harmonics compensation in an islanded ac microgrid," *IEEE Trans. Energy Convers.*, vol. 31, no. 3, pp. 1037–1050, 2016.
- [37] M. Jafari, V. Sarfi, A. Ghasemkhani, H. Livani, L. Yang, H. Xu, and R. Koosha, "Adaptive neural network based intelligent secondary control for microgrids," in *Texas Power and Energy Conf. (TPEC)*, 2018 IEEE. IEEE, 2018, pp. 1–6.
- [38] T. Dragičević, R. Heydari, and F. Blaabjerg, "Super-high bandwidth secondary control of ac microgrids," in *Applied Power Electronics Conf. and Exposition (APEC)*, IEEE. IEEE, 2018, pp. 3036–3042.



- [39] X. Yang, Y. Du, J. Su, L. Chang, Y. Shi, and J. Lai, "An optimal secondary voltage control strategy for an islanded multibus microgrid," *IEEE Journal of Emerg. Sel. Topics Power Electron.*, vol. 4, no. 4, pp. 1236–1246, 2016.
- [40] M. Savaghebi, Q. Shafiee, J. C. Vasquez, and J. M. Guerrero, "Adaptive virtual impedance scheme for selective compensation of voltage unbalance and harmonics in microgrids," in *Power & Energy Soc. General Meeting, IEEE*. IEEE, 2015, pp. 1–5.
- [41] Y. Guan, J. C. Vasquez, and J. M. Guerrero, "Coordinated secondary control for balanced discharge rate of energy storage system in islanded ac microgrids," *IEEE Trans. Ind. Appl.*, vol. 52, no. 6, pp. 5019–5028, 2016.
- [42] A. Micallef, M. Apap, C. Spiteri-Staines, J. M. Guerrero, and J. C. Vasquez, "Reactive power sharing and voltage harmonic distortion compensation of droop controlled single phase islanded microgrids," *IEEE Trans. Smart Grid*, vol. 5, no. 3, pp. 1149–1158, 2014.
- [43] S. Acharya, M. S. El Moursi, A. Al-Hinai, A. S. Al-Sumaiti, and H. Zeineldin, "A control strategy for voltage unbalance mitigation in an islanded microgrid considering demand side management capability," *IEEE Trans. Smart Grid*, vol. 10, no. 3, pp. 2558–2568, 2018.
- [44] S. Liu, X. Wang, and P. X. Liu, "Impact of communication delays on secondary frequency control in an islanded microgrid," *IEEE Trans. Ind. Electron.*, vol. 62, no. 4, pp. 2021–2031, 2015.
- [45] L. Meng, F. Tang, M. Savaghebi, J. C. Vasquez, and J. M. Guerrero, "Tertiary control of voltage unbalance compensation for optimal power quality in islanded microgrids," *IEEE Trans. Energy Convers.*, vol. 29, no. 4, pp. 802–815, 2014.
- [46] A. Milczarek, M. Malinowski, and J. M. Guerrero, "Reactive power management in islanded microgrid: Proportional power sharing in hierarchical droop control," *IEEE Trans. Smart Grid*, vol. 6, no. 4, pp. 1631–1638, 2015.
- [47] E. Smith, D. A. Robinson, and P. Ciufu, "Secondary control of voltage & current unbalance in a multi-bus microgrid using cooperative adjustment of q- droop gains," in *Universities Power Eng. Conf. (AUPEC), 2017 Australasian*. IEEE, 2017, pp. 1–7.
- [48] Q. Shafiee, T. Dragicevic, J. C. Vasquez, J. M. Guerrero, C. Stefanovic, and P. Popovski, "A novel robust communication algorithm for distributed secondary control of islanded microgrids," in *Energy Conversion Congress and Exposition (ECCE), 2013 IEEE*. IEEE, 2013, pp. 4609–4616.
- [49] R. Heydari, T. Dragicevic, and F. Blaabjerg, "High-bandwidth secondary voltage and frequency control of vsc-based ac microgrid," *IEEE Trans. Power Electron.*, 2019.
- [50] Q. Shafiee, J. M. Guerrero, and J. C. Vasquez, "Distributed secondary control for islanded microgrids: a novel approach," *IEEE Trans. Power Electron.*, vol. 29, no. 2, pp. 1018–1031, 2014.
- [51] Q. Shafiee, Č. Stefanović, T. Dragičević, P. Popovski, J. C. Vasquez, and J. M. Guerrero, "Robust networked control scheme for distributed secondary control of islanded microgrids," *IEEE Trans. Ind. Electron.*, vol. 61, no. 10, pp. 5363–5374, 2014.
- [52] R. Heydari, A. Amiri, T. Dragicevic, P. Popovski, and F. Blaabjerg, "High bandwidth distributed secondary control with communication compensation in vsc-based microgrid," in *20th Europ. Conf. on Power Electron. Appl. (EPE'18 ECCE Europe)*. IEEE, 2018, pp. 1–6.
- [53] J. Schiffer, F. Dörfler, and E. Fridman, "Robustness of distributed averaging control in power systems: Time delays & dynamic communication topology," *Automatica*, vol. 80, pp. 261–271, 2017.
- [54] S. Rivero, M. Tucci, J. C. Vasquez, J. M. Guerrero, and G. Ferrari-Trecate, "Stabilizing plug-and-play regulators and secondary coordinated control for ac islanded microgrids with bus-connected topology," *Applied Energy*, vol. 210, pp. 914–924, 2018.
- [55] J. W. Simpson-Porco, F. Dörfler, and F. Bullo, "Synchronization and power sharing for droop-controlled inverters in islanded microgrids," *Automatica*, vol. 49, no. 9, pp. 2603–2611, 2013.
- [56] R. Heydari, M. Alhasheem, T. Dragicevic, and F. Blaabjerg, "Model predictive control approach for distributed hierarchical control of vsc-based microgrids," in *20th Europ. Conf. on Power Electron. Appl. (EPE'18 ECCE Europe)*. IEEE, 2018, pp. 1–7.
- [57] H. Cai and G. Hu, "Consensus-based distributed nonlinear hierarchical control of ac microgrid under switching communication network," in *Control and Automation (ICCA), 12th IEEE Int. Conf. on*. IEEE, 2016, pp. 571–576.
- [58] J. Lai, H. Zhou, X. Lu, and Z. Liu, "Distributed power control for ders based on networked multiagent systems with communication delays," *Neurocomputing*, vol. 179, pp. 135–143, 2016.
- [59] W. Kang, Q. Li, M. Gao, X. Li, J. Wang, R. Xu, and M. Chen, "Distributed secondary control method for islanded microgrids with communication constraints," *IEEE Access*, vol. 6, pp. 5812–5821, 2018.
- [60] X. Lu, X. Yu, J. Lai, J. M. Guerrero, and H. Zhou, "Distributed secondary voltage and frequency control for islanded microgrids with uncertain communication links," *IEEE Trans. Ind. Informat.*, vol. 13, no. 2, pp. 448–460, 2017.
- [61] J. Lai, H. Zhou, X. Lu, X. Yu, and W. Hu, "Droop-based distributed cooperative control for microgrids with time-varying delays," *IEEE Trans. Smart Grid*, vol. 7, no. 4, pp. 1775–1789, 2016.
- [62] P. Martí, M. Velasco, E. X. Martín, M. Castilla, J. Miret, and J. Torres-Martinez, "Performance analysis of frequency restoration for parallel voltage source inverters connected with a realistic communication channel," in *Industrial Informatics (INDIN), IEEE 13th Int. Conf. on*. IEEE, 2015, pp. 191–196.
- [63] P. Martí, M. Velasco, E. X. Martín, L. G. de Vicuña, J. Miret, and M. Castilla, "Performance evaluation of secondary control policies with respect to digital communications properties in inverter-based islanded microgrids," *IEEE Trans. Smart Grid*, vol. 9, no. 3, pp. 2192–2202, 2018.
- [64] M. El Moursi, G. Joos, and C. Abbey, "A secondary voltage control strategy for transmission level interconnection of wind generation," *IEEE Trans. Power Electron.*, vol. 23, no. 3, pp. 1178–1190, 2008.
- [65] L.-Y. Lu and C.-C. Chu, "Consensus-based secondary frequency and voltage droop control of virtual synchronous generators for isolated ac micro-grids," *IEEE Journal on Emerg. Sel. Topics Circuits Syst.*, vol. 5, no. 3, pp. 443–455, 2015.
- [66] R. Han, L. Meng, G. Ferrari-Trecate, E. A. A. Coelho, J. C. Vasquez, and J. M. Guerrero, "Containment and consensus-based distributed coordination control to achieve bounded voltage and precise reactive power sharing in islanded ac microgrids," *IEEE Trans. Ind. Appl.*, vol. 53, no. 6, pp. 5187–5199, 2017.
- [67] S. Shrivastava, B. Subudhi, and S. Das, "Distributed voltage and frequency synchronisation control scheme for islanded inverter-based microgrid," *IET Smart Grid*, vol. 1, no. 2, pp. 48–56, 2018.
- [68] N. T. Janssen, R. W. Wies, and R. A. Peterson, "Frequency regulation by distributed secondary loads on islanded wind-powered microgrids," *IEEE Trans. Sustain. Energy*, vol. 7, no. 3, pp. 1028–1035, 2016.
- [69] Y. Guan, J. C. Vasquez, J. M. Guerrero, Y. Wang, and W. Feng, "Frequency stability of hierarchically controlled hybrid photovoltaic-battery-hydropower microgrids," *IEEE Trans. Ind. Appl.*, vol. 51, no. 6, pp. 4729–4742, 2015.
- [70] C. Li, E. A. A. Coelho, T. Dragicevic, J. M. Guerrero, and J. C. Vasquez, "Multiagent-based distributed state of charge balancing control for distributed energy storage units in ac microgrids," *IEEE Trans. Ind. Appl.*, vol. 53, no. 3, pp. 2369–2381, 2017.
- [71] F. Chen, M. Chen, Q. Li, K. Meng, J. M. Guerrero, and D. Abbott, "Multiagent-based reactive power sharing and control model for islanded microgrids," *IEEE Trans. Sustain. Energy*, vol. 7, no. 3, pp. 1232–1244, 2016.
- [72] A. Micallef, M. Apap, C. Spiteri-Staines, and J. M. Guerrero, "Secondary control for reactive power sharing in droop-controlled islanded microgrids," in *2012 IEEE Int. Symposium on Ind. Electron.*. IEEE, 2012, pp. 1627–1633.
- [73] A. Bidram, A. Davoudi, F. L. Lewis, and Z. Qu, "Secondary control of microgrids based on distributed cooperative control of multi-agent systems," *IET GENER. TRANSM. DIS.*, vol. 7, no. 8, pp. 822–831, 2013.
- [74] Q. Guo, H. Wu, L. Lin, Z. Bai, and H. Ma, "Secondary voltage control for reactive power sharing in an islanded microgrid," *J. POWER ELECTRON.*, vol. 16, no. 1, pp. 329–339, 2016.
- [75] J. W. Simpson-Porco, F. Dörfler, F. Bullo, Q. Shafiee, and J. M. Guerrero, "Stability, power sharing, & distributed secondary control in droop-controlled microgrids," in *Smart Grid Commun. (SmartGridComm), IEEE Int. Conf. on*. IEEE, 2013, pp. 672–677.
- [76] X. Lu, X. Yu, J. Lai, Y. Wang, and J. M. Guerrero, "A novel distributed secondary coordination control approach for islanded microgrids," *IEEE Trans. Smart Grid*, vol. 9, no. 4, pp. 2726–2740, 2018.
- [77] X. Wu, C. Shen, and R. Iravani, "A distributed, cooperative frequency and voltage control for microgrids," *IEEE Trans. Smart Grid*, vol. 9, no. 4, pp. 2764–2776, 2018.
- [78] A. Bidram, A. Davoudi, and F. L. Lewis, "A multiobjective distributed control framework for islanded ac microgrids," *IEEE Trans. Ind. Informat.*, vol. 10, no. 3, pp. 1785–1798, 2014.
- [79] J. Zhou, S. Kim, H. Zhang, Q. Sun, and R. Han, "Consensus-based distributed control for accurate reactive, harmonic, and imbalance

- power sharing in microgrids,” *IEEE Trans. Smart Grid*, vol. 9, no. 4, pp. 2453–2467, 2018.
- [80] M. S. Golsorkhi, Q. Shafiee, D. D.-C. Lu, and J. M. Guerrero, “A distributed control framework for integrated photovoltaic-battery-based islanded microgrids,” *IEEE Trans. Smart Grid*, vol. 8, no. 6, pp. 2837–2848, 2017.
- [81] N. M. Dehkordi, N. Sadati, and M. Hamzeh, “Fully distributed cooperative secondary frequency and voltage control of islanded microgrids,” *IEEE Trans. Energy Convers.*, vol. 32, no. 2, pp. 675–685, 2017.
- [82] M. P. Korukonda, S. R. Mishra, K. Rajawat, and L. Behera, “Hybrid adaptive framework for coordinated control of distributed generators in cyber-physical energy systems,” *IET Cyber-Physical Systems: Theory & Applications*, vol. 3, no. 1, pp. 54–62, 2017.
- [83] S. Trip and C. De Persis, “Distributed optimal load frequency control with non-passive dynamics,” *IEEE Trans. Control Netw. Syst.*, vol. 5, no. 3, pp. 1232–1244, 2017.
- [84] Q. Li, C. Peng, M. Wang, M. Chen, J. M. Guerrero, and D. Abbott, “Distributed secondary control and management of islanded microgrids via dynamic weights,” *IEEE Trans. Smart Grid*, vol. 10, no. 2, pp. 2196–2207, 2018.
- [85] K. Aloheidli and M. S. El Moursi, “Novel coordinated secondary voltage control strategy for efficient utilisation of distributed generations,” *IET RENEW. POWER GEN.*, vol. 8, no. 5, pp. 569–579, 2014.
- [86] W. Liu, W. Gu, Q. Huang, L. Chen, and X. Yuan, “Pinning group consensus-based distributed coordination control for active distribution systems,” *IEEE Access*, vol. 6, pp. 2330–2339, 2018.
- [87] S. Manaffam, M. Talebi, A. Jain, and A. Behal, “Synchronization in networks of identical systems via pinning: Application to distributed secondary control of microgrids,” *IEEE Trans. Control Syst. Technol.*, vol. 25, no. 6, pp. 2227–2234, 2017.
- [88] F. Dörfler, J. W. Simpson-Porco, and F. Bullo, “Breaking the hierarchy: Distributed control and economic optimality in microgrids,” *IEEE Trans. Control Net. Syst.*, vol. 3, no. 3, pp. 241–253, 2016.
- [89] G. Zhang, C. Li, D. Qi, and H. Xin, “Distributed estimation and secondary control of autonomous microgrid,” *IEEE Trans. Power Syst.*, vol. 32, no. 2, pp. 989–998, 2017.
- [90] X. Wang, H. Zhang, and C. Li, “Distributed finite-time cooperative control of droop-controlled microgrids under switching topology,” *IET RENEW. POWER GEN.*, vol. 11, no. 5, pp. 707–714, 2016.
- [91] N. M. Dehkordi, N. Sadati, and M. Hamzeh, “Distributed robust finite-time secondary voltage and frequency control of islanded microgrids,” *IEEE Trans. Power Syst.*, vol. 32, no. 5, pp. 3648–3659, 2017.
- [92] F. Guo, C. Wen, J. Mao, J. Chen, and Y.-D. Song, “Distributed cooperative secondary control for voltage unbalance compensation in an islanded microgrid,” *IEEE Trans. Ind. Informat.*, vol. 11, no. 5, pp. 1078–1088, 2015.
- [93] Z. Deng, Y. Xu, H. Sun, and X. Shen, “Distributed, bounded and finite-time convergence secondary frequency control in an autonomous microgrid,” *IEEE Trans. Smart Grid*, vol. 10, no. 3, pp. 2776–2788, 2018.
- [94] Y. Xu, “Robust finite-time control for autonomous operation of an inverter-based microgrid,” *IEEE Trans. Ind. Informat.*, vol. 13, no. 5, pp. 2717–2725, 2017.
- [95] J. Ni, L. Liu, C. Liu, X. Hu, and S. Li, “Secondary voltage control for microgrids based on fixed-time distributed cooperative control of multi-agent systems,” in *American Control Conf. (ACC)*, IEEE, 2017, pp. 761–766.
- [96] Y. Xu and H. Sun, “Distributed finite-time convergence control of an islanded low-voltage ac microgrid,” *IEEE Trans. Power Syst.*, vol. 33, no. 3, pp. 2339–2348, 2018.
- [97] A. M. Shotorbani, S. Ghassem-Zadeh, B. Mohammadi-Ivatloo, and S. H. Hosseini, “A distributed secondary scheme with terminal sliding mode controller for energy storages in an islanded microgrid,” *Int. Journal of Electrical Power & Energy Systems*, vol. 93, pp. 352–364, 2017.
- [98] A. Bidram, A. Davoudi, F. L. Lewis, and J. M. Guerrero, “Distributed cooperative secondary control of microgrids using feedback linearization,” *IEEE Trans. Power Syst.*, vol. 28, no. 3, pp. 3462–3470, 2013.
- [99] H. Cai and G. Hu, “Distributed nonlinear hierarchical control of ac microgrid via unreliable communication,” *IEEE Trans. Smart Grid*, vol. 9, no. 4, pp. 2429–2441, 2018.
- [100] A. Pilloni, A. Pisano, and E. Usai, “Robust finite-time frequency and voltage restoration of inverter-based microgrids via sliding-mode cooperative control,” *IEEE Trans. Ind. Electron.*, vol. 65, no. 1, pp. 907–917, 2018.
- [101] M. Mahmud, M. Hossain, H. Pota, and A. Oo, “Robust nonlinear distributed controller design for active and reactive power sharing in islanded microgrids,” *IEEE Trans. Energy Convers.*, vol. 29, no. 4, pp. 893–903, 2014.
- [102] G. Lou, W. Gu, W. Sheng, X. Song, and F. Gao, “Distributed model predictive secondary voltage control of islanded microgrids with feedback linearization,” *IEEE Access*, vol. 6, pp. 50 169–50 178, 2018.
- [103] G. Lou, W. Gu, Y. Xu, M. Cheng, and W. Liu, “Distributed mpc-based secondary voltage control scheme for autonomous droop-controlled microgrids,” *IEEE Trans. Sustain. Energy*, vol. 8, no. 2, pp. 792–804, 2017.
- [104] C. Ahumada, R. Cárdenas, D. Sáez, and J. M. Guerrero, “Secondary control strategies for frequency restoration in islanded microgrids with consideration of communication delays,” *IEEE Trans. Smart Grid*, vol. 7, no. 3, pp. 1430–1441, 2016.
- [105] H. Bevrani, M. R. Feizi, and S. Ataee, “Robust frequency control in an islanded microgrid:  $H_\infty$  and  $\mu$  synthesis approaches,” *IEEE Trans. Smart Grid*, vol. 7, no. 2, pp. 706–717, 2016.
- [106] A. Fathi, Q. Shafiee, and H. Bevrani, “Robust frequency control of microgrids using an extended virtual synchronous generator,” *IEEE Trans. Power Syst.*, pp. 1–9, 2018.
- [107] M. P. Korukonda, S. R. Mishra, A. Shukla, and L. Behera, “Handling multi-parametric variations in distributed control of cyber-physical energy systems through optimal communication design,” *IET Cyber-Physical Systems: Theory & Applications*, vol. 2, no. 2, pp. 90–100, 2017.
- [108] L.-Y. Lu, H. J. Liu, and H. Zhu, “Distributed secondary control for isolated microgrids under malicious attacks,” in *North American Power Symposium (NAPS)*, 2016. IEEE, 2016, pp. 1–6.
- [109] N. F. Avila and C.-C. Chu, “Distributed pinning droop control in isolated ac microgrids,” *IEEE Trans. Ind. Appl.*, vol. 53, no. 4, pp. 3237–3249, 2017.
- [110] W. Liu, W. Gu, Y. Xu, Y. Wang, and K. Zhang, “General distributed secondary control for multi-microgrids with both pq-controlled and droop-controlled distributed generators,” *IET GENER. TRANSM. DIS.*, vol. 11, no. 3, pp. 707–718, 2017.
- [111] M. Chen and X. Xiao, “Hierarchical frequency control strategy of hybrid droop/vsg-based islanded microgrids,” *Electric Power Systems Research*, vol. 155, pp. 131–143, 2018.
- [112] H. Bevrani, F. Habibi, P. Babahajyani, M. Watanabe, and Y. Mitani, “Intelligent frequency control in an ac microgrid: Online pso-based fuzzy tuning approach,” *IEEE Trans. Smart Grid*, vol. 3, no. 4, pp. 1935–1944, 2012.
- [113] S. Manaffam, M. Talebi, A. K. Jain, and A. Behal, “Intelligent pinning based cooperative secondary control of distributed generators for microgrid in islanding operation mode,” *IEEE Trans. Power Syst.*, vol. 33, no. 2, pp. 1364–1373, 2018.
- [114] Z. Zhao, P. Yang, J. M. Guerrero, Z. Xu, and T. C. Green, “Multiple-time-scales hierarchical frequency stability control strategy of medium-voltage isolated microgrid,” *IEEE Trans. Power Electron.*, vol. 31, no. 8, pp. 5974–5991, 2016.
- [115] J. Schiffer, T. Seel, J. Raisch, and T. Sezi, “Voltage stability and reactive power sharing in inverter-based microgrids with consensus-based distributed voltage control,” *IEEE Trans. Contr. Sys. Technol.*, vol. 24, no. 1, pp. 96–109, 2016.
- [116] J. Schiffer, E. Fridman, R. Ortega, and J. Raisch, “Stability of a class of delayed port-hamiltonian systems with application to microgrids with distributed rotational and electronic generation,” *Automatica*, vol. 74, pp. 71–79, 2016.
- [117] M. P. Contzen and J. Raisch, “Reactive power consensus in microgrids,” in *Control Conf. (ECC), 2016 European*. IEEE, 2016, pp. 334–339.
- [118] F. Guo, C. Wen, J. Mao, and Y.-D. Song, “Distributed secondary voltage and frequency restoration control of droop-controlled inverter-based microgrids,” *IEEE Trans. Ind. Electron.*, vol. 62, no. 7, pp. 4355–4364, 2015.
- [119] F. Tang, J. M. Guerrero, J. C. Vasquez, D. Wu, and L. Meng, “Distributed active synchronization strategy for microgrid seamless reconnection to the grid under unbalance and harmonic distortion,” *IEEE Trans. Smart Grid*, vol. 6, no. 6, pp. 2757–2769, 2015.
- [120] F. Dörfler and S. Grammatico, “Gather-and-broadcast frequency control in power systems,” *Automatica*, vol. 79, pp. 296–305, 2017.
- [121] G. Lou, W. Gu, J. Wang, W. Sheng, and L. Sun, “Optimal design for distributed secondary voltage control in islanded microgrids: Communication topology and controller,” *IEEE Trans. Power Syst.*, vol. 34, no. 2, pp. 968–981, 2019.
- [122] S. Weng, D. Yue, C. Dou, J. Shi, and C. Huang, “Distributed event-triggered cooperative control for frequency and voltage stability and power sharing in isolated inverter-based microgrid,” *IEEE Trans. Cybern.*, no. 99, pp. 1–13, 2018.

- [123] J. Shi, D. Yue, and S. Weng, "Distributed event-triggered mechanism for secondary voltage control with microgrids," *T. I. MEAS. CONTROL*, vol. 41, no. 6, pp. 1553–1561, 2019.
- [124] X. Ge and Q.-L. Han, "Distributed formation control of networked multi-agent systems using a dynamic event-triggered communication mechanism," *IEEE Trans. Ind. Electron.*, vol. 64, no. 10, pp. 8118–8127, 2017.
- [125] Y. Fan, G. Hu, and M. Egerstedt, "Distributed reactive power sharing control for microgrids with event-triggered communication," *IEEE Trans. Control Syst. Technol.*, vol. 25, no. 1, pp. 118–128, 2017.
- [126] M. S. Mahmoud and M. S. U. Rahman, "Event triggered of microgrid control with communication and control optimization," *Journal of the Franklin Institute*, vol. 353, no. 16, pp. 4114–4132, 2016.
- [127] C.-x. Dou, B. Liu, and J. M. Guerrero, "Event-triggered hybrid control based on multi-agent system for microgrids," *IET GENER. TRANSM. DIS.*, vol. 8, no. 12, pp. 1987–1997, 2014.
- [128] B. Abdolmaleki, A. Seifi, M. M. Arefi, and Q. Shafiee, "Event-triggered voltage control of inverter-based microgrids," in *Power Electron. and Drives Syst. Technol. Conf. (PEDSTC)*, 2018 9th Annu. IEEE, 2018, pp. 522–528.
- [129] C. Dou, B. Liu, and J. M. Guerrero, "Mas based event-triggered hybrid control for smart microgrids," in *Ind. Electron. Soc., IECON 39th Annu. Conf. of the IEEE*. IEEE, 2013, pp. 1712–1717.
- [130] Y. Fan, M. Sheng, C. Dong, and Y. Zhang, "Sampling-based event-triggered control for distributed generators," in *Control And Decision Conf. (CDC)*, 29th Chinese. IEEE, 2017, pp. 5556–5560.
- [131] Y. Fan, C. Zhang, and C. Song, "Sampling-based self-triggered coordination control for multi-agent systems with application to distributed generators," *Int. Journal of Systems Science*, pp. 1–15, 2018.
- [132] M. Chen and X. Xiao, "Secondary voltage control in islanded microgrids using event-triggered control," *IET GENER. TRANSM. DIS.*, vol. 12, no. 8, pp. 1872–1878, 2018.
- [133] M. Chen, X. Xiao, and J. M. Guerrero, "Secondary restoration control of islanded microgrids with a decentralized event-triggered strategy," *IEEE Trans Ind. Informat.*, vol. 14, no. 9, pp. 3870–3880, 2018.
- [134] M. Tahir and S. K. Mazumder, "Self-triggered communication enabled control of distributed generation in microgrids," *IEEE Trans. Ind. Inf.*, vol. 11, no. 2, pp. 441–449, 2015.
- [135] M. Yazdani and A. Mehrizi-Sani, "Washout filter-based power sharing," *IEEE Trans. Smart Grid*, vol. 7, no. 2, pp. 967–968, 2016.
- [136] Y. Han, H. Li, L. Xu, X. Zhao, and J. M. Guerrero, "Analysis of washout filter-based power sharing strategy an equivalent secondary controller for islanded microgrid without lbc lines," *IEEE Trans. Smart Grid*, vol. 9, no. 5, pp. 4061–4076, 2018.
- [137] Y. Sun, X. Hou, J. Yang, H. Han, M. Su, and J. M. Guerrero, "New perspectives on droop control in ac microgrid," *IEEE Trans. Ind. Electron.*, vol. 64, no. 7, pp. 5741–5745, 2017.
- [138] J. Lu, M. Savaghebi, and J. M. Guerrero, "Second order washout filter based power sharing strategy for uninterruptible power supply," in *Ind. Electron. Soc., IECON 43rd Annu. Conf. of the IEEE*. IEEE, 2017, pp. 7854–7859.
- [139] M. Castilla, A. Camacho, J. Miret, M. Velasco, and P. Martí, "Local secondary control for inverter-based islanded microgrids with accurate active-power sharing under high load conditions," *IEEE Trans. Ind. Electron.*, vol. 66, no. 4, pp. 2529–2539, 2018.
- [140] J. M. Rey, P. Martí, M. Velasco, J. Miret, and M. Castilla, "Secondary switched control with no communications for islanded microgrids," *IEEE Trans. Ind. Electron.*, vol. 64, no. 11, pp. 8534–8545, 2017.
- [141] M. Velasco, P. Martí, A. Camacho, J. Miret, and M. Castilla, "Synchronization of local integral controllers for frequency restoration in islanded microgrids," in *Ind. Electron. Soc., IECON 42nd Annu. Conf. of the IEEE*. IEEE, 2016, pp. 3906–3911.
- [142] Z. Zhang, C. Dou, D. Yue, B. Zhang, and W. Luo, "A decentralized control method for frequency restoration and accurate reactive power sharing in islanded microgrids," *Journal of the Franklin Institute*, vol. 355, no. 17, pp. 8874–8890, 2018.
- [143] Y. Khayat, M. Naderi, Q. Shafiee, M. Fathi, H. Bevrani, T. Dragicevic, and F. Blaabjerg, "Communication-less optimal frequency control of islanded microgrids," in *20th Europ. Conf. on Power Electron. Appl. (EPE'18 ECCE Europe)*. IEEE, 2018, pp. 1–6.
- [144] Y. Khayat, M. Naderi, Q. Shafiee, Y. Batmani, M. Fathi, J. M. Guerrero, and H. Bevrani, "Decentralized optimal frequency control in autonomous microgrids," *IEEE Trans. Power Syst.*, vol. 34, no. 3, pp. 2345–2353, 2018.
- [145] E. Weitenberg, Y. Jiang, C. Zhao, E. Mallada, C. De Persis, and F. Dörfler, "Robust decentralized secondary frequency control in power systems: Merits and trade-offs," *IEEE Trans. Autom. Control*, 2018.
- [146] W. Gu, G. Lou, W. Tan, and X. Yuan, "A nonlinear state estimator-based decentralized secondary voltage control scheme for autonomous microgrids," *IEEE Trans. Power Syst.*, vol. 32, no. 6, pp. 4794–4804, 2017.
- [147] Y. Wang, Z. Chen, X. Wang, Y. Tian, Y. Tan, and C. Yang, "An estimator-based distributed voltage-predictive control strategy for ac islanded microgrids," *IEEE Trans. Power Electron.*, vol. 30, no. 7, pp. 3934–3951, 2015.
- [148] P. Le Minh, H. P. T. Xuan, D. H. V. Duc, and H. N. Minh, "Control of power inverter in islanded microgrids based on online line impedance estimation," in *Syst. Sci. and Eng. (ICSSE), Int. Conf. on*. IEEE, 2017, pp. 180–185.
- [149] G. Lou, W. Gu, L. Wang, B. Xu, M. Wu, and W. Sheng, "Decentralised secondary voltage and frequency control scheme for islanded microgrid based on adaptive state estimator," *IET GENER. TRANSM. DIS.*, vol. 11, no. 15, pp. 3683–3693, 2017.
- [150] N. Xia, H. B. Gooi, S. Chen, and W. Hu, "Decentralized state estimation for hybrid ac/dc microgrids," *IEEE Systems Journal*, vol. 12, no. 1, pp. 434–443, 2018.
- [151] M. M. Rana and L. Li, "An overview of distributed microgrid state estimation and control for smart grids," *Sensors*, vol. 15, no. 2, pp. 4302–4325, 2015.
- [152] A. Morattab, O. Akhrif, and M. Saad, "Decentralised coordinated secondary voltage control of multi-area power grids using model predictive control," *IET GENER. TRANSM. DIS.*, vol. 11, no. 18, pp. 4546–4555, 2017.
- [153] H. Bevrani, *Robust power system frequency control*. Springer, 2014.
- [154] F. Milano, F. Dörfler, G. Hug, D. J. Hill, and G. Verbič, "Foundations and challenges of low-inertia systems," in *Power Syst. Comput. Conf. (PSCC)*. IEEE, 2018, pp. 1–25.
- [155] H. Bevrani and J. Raisch, "On virtual inertia application in power grid frequency control," *Energy Procedia*, vol. 141, pp. 681–688, 2017.
- [156] J. W. Simpson-Porco, F. Dörfler, and F. Bullo, "Voltage stabilization in microgrids via quadratic droop control," *IEEE Trans. Autom. Control*, vol. 62, no. 3, pp. 1239–1253, 2017.
- [157] M. Farivar, R. Neal, C. Clarke, and S. Low, "Optimal inverter var control in distribution systems with high pv penetration," in *2012 IEEE Power and Energy Society general meeting*. IEEE, 2012, pp. 1–7.
- [158] K. Mandal and S. Banerjee, "Synchronization phenomena in interconnected power electronic systems," *IEEE Trans. Circuits Syst. II: Exp. Briefs*, vol. 63, no. 2, pp. 221–225, 2016.
- [159] S. Abhinav, I. D. Schizas, F. Ferrese, and A. Davoudi, "Optimization-based ac microgrid synchronization," *IEEE Trans. Ind. Informat.*, vol. 13, no. 5, pp. 2339–2349, 2017.
- [160] C. Cho, J.-H. Jeon, J.-Y. Kim, S. Kwon, K. Park, and S. Kim, "Active synchronizing control of a microgrid," *IEEE Trans. Power Electron.*, vol. 26, no. 12, pp. 3707–3719, 2011.
- [161] K. Mandal and S. Banerjee, "Synchronization phenomena in microgrids with capacitive coupling," *IEEE Journal on Emerg. Sel. Topics Circuits Syst.*, vol. 5, no. 3, pp. 364–371, 2015.
- [162] S. A. Taher, M. Zolfaghari, C. Cho, M. Abedi, and M. Shahidehpour, "A new approach for soft synchronization of microgrid using robust control theory," *IEEE Trans. Power Del.*, vol. 32, no. 3, pp. 1370–1381, 2017.
- [163] S. Abhinav, H. Modares, F. L. Lewis, F. Ferrese, and A. Davoudi, "Synchrony in networked microgrids under attacks," *IEEE Trans. Smart Grid*, 2017.
- [164] M. Andreasson, D. V. Dimarogonas, K. H. Johansson, and H. Sandberg, "Distributed vs. centralized power systems frequency control under unknown load changes," in *European Control Conference*, Zürich, Switzerland, Jul. 2013, pp. 3524–3529.
- [165] E. Tegling, M. Andreasson, J. W. Simpson-Porco, and H. Sandberg, "Improving performance of droop-controlled microgrids through distributed PI-control," in *American Control Conference*, Boston, MA, USA, Jul. 2016, pp. 2321–2327.
- [166] M. Andreasson, E. Tegling, H. Sandberg, and K. H. Johansson, "Coherence in synchronizing power networks with distributed integral control," in *2017 IEEE 56th Annual Conference on Decision and Control (CDC)*, Melbourne, Australia, Dec. 2017, pp. 6327–6333.
- [167] H. Flamme, E. Tegling, and H. Sandberg, "Performance limitations of distributed integral control in power networks under noisy measurements," in *2018 Annual American Control Conference (ACC)*, Milwaukee, WI, USA, Jun. 2018, pp. 5380–5386.
- [168] S. T. Cady, A. D. Domínguez-García, and C. N. Hadjicostis, "A distributed generation control architecture for islanded ac microgrids," *IEEE Trans. Control Syst. Technol.*, vol. 23, no. 5, pp. 1717–1735, 2015.

- [169] R. Olfati-Saber, J. A. Fax, and R. M. Murray, "Consensus and cooperation in networked multi-agent systems," *Proc. of the IEEE*, vol. 95, no. 1, pp. 215–233, 2007.
- [170] E. A. A. Coelho, D. Wu, J. M. Guerrero, J. C. Vasquez, T. Dragicevic, C. Stefanovic, and P. Popovski, "Small-signal analysis of the microgrid secondary control considering a communication time delay," *IEEE Trans. Ind. Electron.*, vol. 63, no. 10, pp. 6257–6269, 2016.
- [171] W. Heemels, K. H. Johansson, and P. Tabuada, "An introduction to event-triggered and self-triggered control," in *Decision and Control (CDC), IEEE 51st Annu. Conf. on*. IEEE, 2012, pp. 3270–3285.
- [172] G. S. Seyboth, D. V. Dimarogonas, and K. H. Johansson, "Event-based broadcasting for multi-agent average consensus," *Automatica*, vol. 49, no. 1, pp. 245–252, 2013.
- [173] D. V. Dimarogonas, E. Frazzoli, and K. H. Johansson, "Distributed event-triggered control for multi-agent systems," *IEEE Transactions on Automatic Control*, vol. 57, no. 5, pp. 1291–1297, 2011.
- [174] E. Garcia, Y. Cao, H. Yu, P. Antsaklis, and D. Casbeer, "Decentralised event-triggered cooperative control with limited communication," *Int. J. Control*, vol. 86, no. 9, pp. 1479–1488, 2013.
- [175] Y. Cheng and V. Ugrinovskii, "Event-triggered leader-following tracking control for multivariable multi-agent systems," *Automatica*, vol. 70, pp. 204–210, 2016.
- [176] W. Zhu and Z.-P. Jiang, "Event-based leader-following consensus of multi-agent systems with input time delay," *IEEE Trans. Autom. Control*, vol. 60, no. 5, pp. 1362–1367, 2014.
- [177] F. Chen, Z. Chen, L. Xiang, Z. Liu, and Z. Yuan, "Reaching a consensus via pinning control," *Automatica*, vol. 45, no. 5, pp. 1215–1220, 2009.
- [178] J. Schiffer, R. Ortega, C. A. Hans, and J. Raisch, "Droop-controlled inverter-based microgrids are robust to clock drifts," in *Proc. of the American Control Conf.* IEEE, 2015, pp. 2341–2346.
- [179] J. Torres-Martínez, M. Castilla, J. Miret, M. Moradi-Ghahderijani, and J. M. Rey, "Experimental study of clock drift impact over droop-free distributed control for industrial microgrids," in *Ind. Electron. Soc., IECON 43rd Annu. Conf. of the IEEE*. IEEE, 2017, pp. 2479–2484.
- [180] A. Krishna, C. A. Hans, J. Schiffer, J. Raisch, and T. Kral, "Steady state evaluation of distributed secondary frequency control strategies for microgrids in the presence of clock drifts," in *Control and Automation (MED), 25th Mediterranean Conf. on*. IEEE, 2017, pp. 508–515.
- [181] J. Schiffer, C. A. Hans, T. Kral, R. Ortega, and J. Raisch, "Modeling, analysis, and experimental validation of clock drift effects in low-inertia power systems," *IEEE Trans. Ind. Electron.*, vol. 64, no. 7, pp. 5942–5951, 2017.
- [182] C. X. Rosero, H. Carrasco, M. Velasco, and P. Martí, "Impact of clock drifts on active power sharing and frequency regulation in distributed-averaging secondary control for islanded microgrids," in *Power, Electron. Comput. (ROPEC), IEEE Int. Autumn Meeting on*. IEEE, 2017, pp. 1–6.
- [183] M. Castilla, A. Camacho, P. Martí, M. Velasco, and M. M. Ghahderijani, "Impact of clock drifts on communication-free secondary control schemes for inverter-based islanded microgrids," *IEEE Trans. Ind. Electron.*, vol. 65, no. 6, pp. 4739–4749, 2018.
- [184] W. Heemels, R. Postoyan, M. Donkers, A. R. Teel, A. Anta, P. Tabuada, and D. Nešić, "Periodic event-triggered control," *Event-based control and signal processing*, pp. 105–119, 2015.
- [185] W. H. Heemels, M. Donkers, and A. R. Teel, "Periodic event-triggered control for linear systems," *IEEE Trans. Autom. Control*, vol. 58, no. 4, pp. 847–861, 2013.
- [186] H. Zhang, G. Feng, H. Yan, and Q. Chen, "Observer-based output feedback event-triggered control for consensus of multi-agent systems," *IEEE Trans. Ind. Electron.*, vol. 61, no. 9, pp. 4885–4894, 2014.
- [187] A. Girard, "Dynamic triggering mechanisms for event-triggered control," *IEEE Trans. Autom. Control*, vol. 60, no. 7, pp. 1992–1997, 2015.
- [188] D. Yue, E. Tian, and Q.-L. Han, "A delay system method for designing event-triggered controllers of networked control systems," *IEEE Trans. Autom. Control*, vol. 58, no. 2, pp. 475–481, 2013.
- [189] X.-M. Zhang, Q.-L. Han, and B.-L. Zhang, "An overview and deep investigation on sampled-data-based event-triggered control and filtering for networked systems," *IEEE Trans. Ind. Informat.*, vol. 13, no. 1, pp. 4–16, 2017.
- [190] A. Selivanov and E. Fridman, "Event-triggered  $h_\infty$  control: A switching approach," *IEEE Trans. Autom. Control*, vol. 61, no. 10, pp. 3221–3226, 2016.
- [191] J. Han and D.-K. Jeong, "A practical implementation of IEEE 1588-2008 transparent clock for distributed measurement and control systems," *IEEE Trans. Instrum. Meas.*, vol. 59, no. 2, pp. 433–439, 2010.
- [192] J. Eidson and K. Lee, "IEEE 1588 standard for a precision clock synchronization protocol for networked measurement and control systems," in *Sensors for Industry Conf., 2nd ISA/IEEE*. IEEE, July, 2002, pp. 98–105.
- [193] J. Rocabert, A. Luna, F. Blaabjerg, and P. Rodriguez, "Control of power converters in ac microgrids," *IEEE Trans. Power Electron.*, vol. 27, no. 11, pp. 4734–4749, 2012.
- [194] L. Schenato and F. Fiorentin, "age timesynch: A consensus-based protocol for clock synchronization in wireless sensor networks," *Automatica*, vol. 47, no. 9, pp. 1878–1886, 2011.
- [195] C. Lu and A. W. Czanderna, *Applications of piezoelectric quartz crystal microbalances*. Elsevier, 2012, vol. 7.
- [196] P. Martí, J. Torres-Martínez, C. X. Rosero, M. Velasco, J. Miret, and M. Castilla, "Analysis of the effect of clock drifts on frequency regulation and power sharing in inverter-based islanded microgrids," *IEEE Trans. Power Electron.*, vol. 33, no. 12, pp. 10363–10379, 2018.
- [197] R. Heydari, Y. Khayat, M. Naderi, A. Anvari-Moghaddam, T. Dragicevic, and F. Blaabjerg, "A decentralized adaptive control method for frequency regulation and power sharing in autonomous microgrids," in *2019 IEEE 28th International Symposium on Industrial Electronics (ISIE)*. IEEE, June 2019, pp. 2427–2432.
- [198] Y. Khayat, R. Heydari, M. Naderi, T. Dragicevic, F. Blaabjerg, and H. Bevrani, "Estimation-based consensus approach for decentralized frequency control of ac microgrids," in *21th Europ. Conf. on Power Electron. Appl. (EPE'19 ECCE Europe)*. IEEE, 2019, pp. 1–6.
- [199] K. Dehghanpour, Z. Wang, J. Wang, Y. Yuan, and F. Bu, "A survey on state estimation techniques and challenges in smart distribution systems," *IEEE Trans. Smart Grid*, vol. 10, no. 2, pp. 2312–2322, 2018.
- [200] D. A. Haughton and G. T. Heydt, "A linear state estimation formulation for smart distribution systems," *IEEE Trans. Power Syst.*, vol. 28, no. 2, pp. 1187–1195, 2013.
- [201] S. Bhela, V. Kekatos, and S. Veeramachaneni, "Enhancing observability in distribution grids using smart meter data," *IEEE Trans. Smart Grid*, vol. 9, no. 6, pp. 5953–5961, 2017.
- [202] M. Chlela, D. Mascarella, G. Joós, and M. Kassouf, "Fallback control for isochronous energy storage systems in autonomous microgrids under denial-of-service cyber-attacks," *IEEE Trans. Smart Grid*, vol. 9, no. 5, pp. 4702–4711, 2018.
- [203] S. Sahoo, S. Mishra, J. C.-H. Peng, and T. Dragicevic, "A stealth cyber attack detection strategy for dc microgrids," *IEEE Trans. Power Electron.*, vol. 34, no. 8, pp. 8162–8174, 2018.
- [204] F. Pasqualetti, F. Dörfler, and F. Bullo, "Attack detection and identification in cyber-physical systems," *IEEE Trans. Autom. Control*, vol. 58, no. 11, pp. 2715–2729, 2013.
- [205] S. Mehrdad, S. Mousavian, G. Madraki, and Y. Dvorkin, "Cyber-physical resilience of electrical power systems against malicious attacks: a review," *Current Sustainable/Renewable Energy Reports*, vol. 5, no. 1, pp. 14–22, 2018.
- [206] R. M. Jüngers, A. Kundu, and W. Heemels, "Observability and controllability analysis of linear systems subject to data losses," *IEEE Trans. Autom. Control*, vol. 63, no. 10, pp. 3361–3376, 2017.
- [207] E. van Horssen, S. Prakash, D. Antunes, and W. Heemels, "Event-driven control with deadline optimization for linear systems with stochastic delays," *IEEE Trans. Control Netw. Syst.*, vol. 5, no. 4, pp. 1819–1829, 2017.
- [208] M. Naderi, Y. Khayat, Q. Shafiee, T. Dragicevic, H. Bevrani, and F. Blaabjerg, "Interconnected autonomous ac microgrids via back-to-back converters part i: Small-signal modeling," *IEEE Trans. Power Electron.*, 2019.



**Yousef Khayat** (S' 16) received the B.Sc. degree from Urmia University, Urmia, Iran, and the M.Sc. (Hons.) degree from the Iran University of Science and Technology (IUST), Tehran, Iran, both in electrical engineering, in 2012 and 2014, respectively. He is currently working toward the Ph.D. degree in Electrical Engineering at Aalborg University, Aalborg, Denmark. His research interests include Microgrid dynamics and control, robust, predictive, and nonlinear control for application of power electronics in distributed systems.





**Qobad Shafiee** (S'13 - M'15 - SM'17) received PhD degree in electrical engineering from the Department of Energy Technology, Aalborg University (Denmark) in 2014. He is currently an Assistant Professor, Director of International Relations, and Program Co-Leader of the Smart/Micro Grids Research Center at the University of Kurdistan, Sanandaj, Iran, where he was a lecturer from 2007 to 2011. In 2014, he was a Visiting Scholar with the Electrical Engineering Department, the University of Texas at Arlington, Arlington, TX, USA. He was a

Post-Doctoral Fellow with the Department of Energy Technology, Aalborg University in 2015. His current research interests include modeling, energy management, control of power electronics-based systems and microgrids, and model predictive and optimal control of modern power systems.



**John W. Simpson-Porco** (S'11–M'18) received the B.Sc. degree in engineering physics from Queen's University, Kingston, ON, Canada in 2010, and the Ph.D. degree in mechanical engineering from the University of California at Santa Barbara, Santa Barbara, CA, USA in 2015.

He is currently an Assistant Professor of Electrical and Computer Engineering at the University of Waterloo, Waterloo, ON, Canada. He was previously a visiting scientist with the Automatic Control Laboratory at ETH Zürich, Zürich, Switzerland. His research focuses on feedback control theory and applications of control in modernized power grids.

Prof. Simpson-Porco is a recipient of the 2012–2014 IFAC Automatica Prize and the Center for Control, Dynamical Systems and Computation Best Thesis Award and Outstanding Scholar Fellowship.



**Rasool Heydari** (S'16-M'19) received the Ph.D. degree in electrical engineering from the Department of Energy Technology, Aalborg University, Denmark, in 2019. He was also a visiting researcher with ABB Corporate Research, Västerås, Sweden, in 2019. He is currently a Post-Doctoral Fellow with the Department of Electrical Engineering, the Mads Clausen Institute, University of Southern Denmark, Odense, Denmark. His principal field of interest include control, stability and dynamic analysis of power electronic systems, mainly distributed and

grid-connected converters and microgrid.



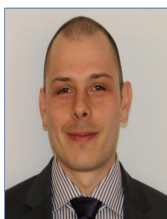
**Mobin Naderi** (S'16) was born in Paveh, Iran. He received the B.Sc. and M.Sc. degrees in Electrical Engineering from Tabriz University, Tabriz, Iran, in 2012 and Iran University of Science and Technology, Tehran, Iran, in 2014. He was a Visiting PhD student with Department of Energy Technology, Aalborg University, Aalborg, Denmark. He is now working toward the Ph.D. degree in the control of power systems at the University of Kurdistan, Iran. His research interests focus on robust control methods, and modeling, stability and control of autonomous

and interconnected AC microgrids.



**Florian Dörfler** is an Associate Professor at the Automatic Control Laboratory at ETH Zürich. He received his Ph.D. degree in Mechanical Engineering from the University of California at Santa Barbara in 2013, and a Diplom degree in Engineering Cybernetics from the University of Stuttgart in 2008. From 2013 to 2014 he was an Assistant Professor at the University of California Los Angeles. His primary research interests are centered around control, optimization, and system theory with applications in energy and power systems. His students were

winners or finalists for Best Student Paper awards at the European Control Conference (2013, 2019), the American Control Conference (2016), and the PES PowerTech Conference (2017). His articles received the 2010 ACC Student Best Paper Award, the 2011 O. Hugo Schuck Best Paper Award, the 2012–2014 Automatica Best Paper Award, and the 2016 IEEE Circuits and Systems Guillemín-Cauer Best Paper Award. He is a recipient of the 2009 Regents Special International Fellowship, the 2011 Peter J. Frenkel Foundation Fellowship, and the 2015 UCSB ME Best PhD award.



**Tomislav Dragičević** (S'09 - M'13 - SM'17) received the M.Sc. and the industrial Ph.D. degrees in Electrical Engineering from the Faculty of Electrical Engineering, Zagreb, Croatia, in 2009 and 2013, respectively. From 2013 until 2016 he has been a Postdoctoral research associate at Aalborg University, Denmark. From March 2016 he is an Associate Professor at Aalborg University, Denmark where he leads an Advanced Control Lab.

He made a guest professor stay at Nottingham University, UK during spring/summer of 2018. His principal field of interest is design and control of microgrids, and application of advanced modeling and control concepts to power electronic systems. He has authored and co-authored more than 180 technical papers (more than 80 of them are published in international journals, mostly IEEE Transactions) in his domain of interest, 8 book chapters and a book in the field. He serves as Associate Editor in the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, in IEEE Emerging and Selected Topics in Power Electronics and in IEEE Industrial Electronics Magazine. Dr. Dragičević is a recipient of the Končar prize for the best industrial PhD thesis in Croatia, and a Robert Mayer Energy Conservation award



**Mohammad Fathi** received the M.Sc. and the Ph.D. degrees in electrical engineering from Amirkabir University of Technology, Tehran, Iran in 2003 and 2010, respectively. From 2003 to 2006, he was a Lecturer with the Department of Electrical Engineering, University of Kurdistan, Sanandaj, Iran, where he is currently working as an Associate Professor. He conducted a part of his Ph.D. research work in the Communications and Networking Theory Laboratory, Royal Institute of Technology, Stockholm, Sweden from February 2010 to November 2010. His

current research interests include smart grid communications and control, wireless network resource allocation, and optimization.



**Frede Blaabjerg** (S'89 - M'88 - SM'97 - F'03) was with ABB-Scandia, Randers, Denmark, from 1987 to 1988. From 1988 to 1992, he got the PhD degree in Electrical Engineering at Aalborg University in 1995. He became an Assistant Professor in 1992, an Associate Professor in 1996, and a Full Professor of power electronics and drives in 1998. From 2017 he became a Villum Investigator. He is honoris causa at University Politehnica Timisoara (UPT), Romania and Tallinn Technical University (TTU) in Estonia.

His current research interests include power electronics and its applications such as in wind turbines, PV systems, reliability, harmonics and adjustable speed drives. He has published more than 600 journal papers in the fields of power electronics and its applications. He is the co-author of four monographs and editor of ten books in power electronics and its applications.

He has received 31 IEEE Prize Paper Awards, the IEEE PELS Distinguished Service Award in 2009, the EPE-PEMC Council Award in 2010, the IEEE William E. Newell Power Electronics Award 2014, the Villum Kann Rasmussen Research Award 2014 and the Global Energy Prize in 2019. He was the Editor-in-Chief of the IEEE TRANSACTIONS ON POWER ELECTRONICS from 2006 to 2012. He has been Distinguished Lecturer for the IEEE Power Electronics Society from 2005 to 2007 and for the IEEE Industry Applications Society from 2010 to 2011 as well as 2017 to 2018. In 2019-2020 he serves a President of IEEE Power Electronics Society. He is Vice-President of the Danish Academy of Technical Sciences too. He is nominated in 2014-2018 by Thomson Reuters to be between the most 250 cited researchers in Engineering in the world.



**Hassan Bevrani** (S'90 - M'04 - SM'08) received PhD degree in electrical engineering from Osaka University (Japan) in 2004. Currently, he is a full professor and the Program Leader of *Smart/Micro Grids Research Center* (SMGRC) at the University of Kurdistan (UOK). Over the years, he has worked as senior research fellow and visiting professor with Osaka University, Kumamoto University (Japan), Queensland University of Technology (Australia), Kyushu Institute of Technology (Japan), Centrale Lille (France), and Technical University of Berlin

(Germany). Prof. Bevrani is the author of 6 international books, 15 book chapters, and more than 300 journal/conference papers. His current research interests include smart grid operation and control, power systems stability and optimization, Microgrid dynamics and control, and Intelligent/robust control applications in power electric industry.



**Josep M. Guerrero** (S'01 - M'04 - SM'08 - F'15) received the B.S. degree in telecommunications engineering, the M.S. degree in electronics engineering, and the Ph.D. degree in power electronics from the Technical University of Catalonia, Barcelona, in 1997, 2000, and 2003, respectively. Since 2011, he has been a Full Professor with the Department of Energy Technology, Aalborg University, Denmark, where he is responsible for the Microgrid Research Program. From 2014, he was a Chair Professor with Shandong University; from 2015, he was a

Distinguished Guest Professor with Hunan University; and from 2016, he was a Visiting Professor Fellow with Aston University, U.K., and also a Guest Professor with the Nanjing University of Posts and Telecommunications. Since 2019, he has also been a Villum Investigator with The Villum Foundation, which supports the Centre for Research on Microgrids (CROM), Aalborg University, where he has also been the Founder and the Director.

His research interests include different microgrid aspects, including power electronics, distributed energy-storage systems, hierarchical and cooperative control, energy management systems, smart metering, and the Internet of Things for AC/DC microgrid clusters and islanded minigrids, especially focused on maritime microgrids for electrical ships, vessels, ferries, and seaports. He is an Associate Editor for a number of the IEEE Transactions.

He has published more than 500 journal articles in the fields of microgrids and renewable energy systems, which are cited more than 40,000 times. He received the Best Paper Award of the IEEE Transactions on Energy Conversion, from 2014 to 2015, the Best Paper Prize of IEEE-PES, in 2015, and the Best Paper Award of the Journal of Power Electronics, in 2016. During five consecutive years, from 2014 to 2018, he was awarded by Clarivate Analytics (former Thomson Reuters) as Highly Cited Researcher. In 2015, he was elevated as the IEEE Fellow for his contributions on distributed power systems and microgrids.